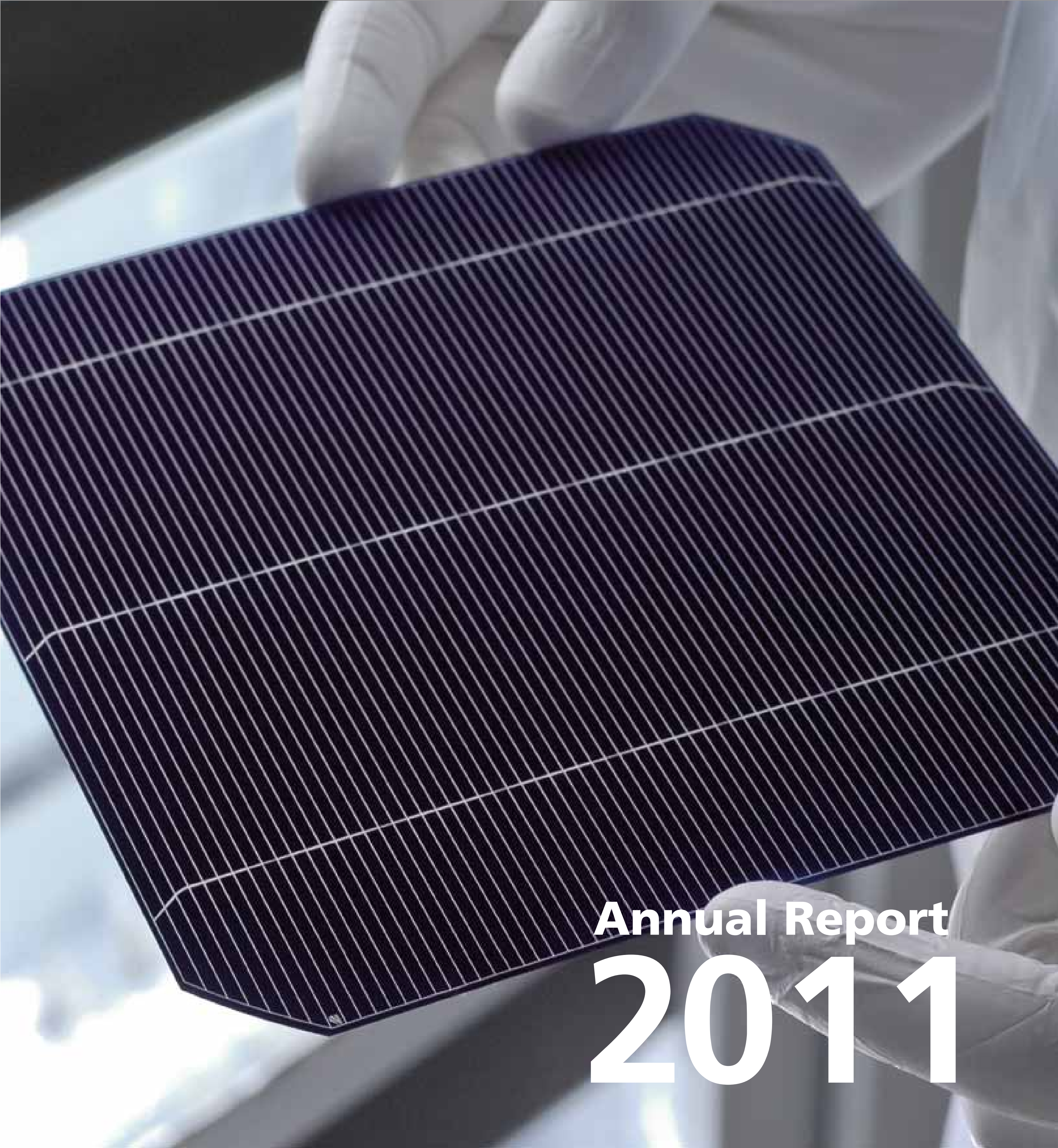
Fraunhofer ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE



Annual Report 2011

Cover:

Passivated Metal Wrap-Through (MWT) solar cell, which combines the advantages of a back-contact solar cell with those of surface passivation in a single solar cell. To minimize shading of the front surface, the usual broad bus bars of conventional solar cells were relocated from the front to the back of the cell. The front contact grid is connected electrically through perforations in the cell to the contacts on the back surface by so-called "vias". Only very thin bus bars remain on the front surface to connect the individual contact grid fingers electrically with the vias. The highest efficiency value of 20.6 % that has been measured to date for large-area p-type solar cells was achieved in 2011 with this type of cell technology. The work was supported by the German Federal Ministry for the Environment, Nature, Conservation and Reactor Safety (BMU).

FOREWORD

In 2011 Fraunhofer ISE celebrated its 30th anniversary. This is a milestone we all are proud of and which we celebrated with invited guests, our partners and supporters from business, industry and politics and, of course, our staff. 2011 was earmarked by the tragic nuclear disaster in Japan and the subsequent decision in Germany to phase out nuclear power in the near future.

"In the aftermath of the Chernobyl disaster and more recently Fukushima, governments and the public sector turn their attention to solar energy", remarks the founder of Fraunhofer ISE Prof Dr Adolf Goetzberger during an interview on the occasion of the Institute's 30th anniversary. One can not better describe the first weeks and months in 2011. When this annual report appears, one year will have already passed since the reactor accident in Fukushima. 2011 was a year marked by worldwide shock, after which the potential of the renewable energy and the necessity of an energy turnaround rooted itself firmly in the public consciousness. Especially in Germany, the renewable energy market and the process towards an energy turnaround have gained speed and developed their own dynamics since the initial moratorium and the subsequent plan-of-action to phase out nuclear power. Today we stand before an exciting period of transformation as well as many challenges. In a co-operative effort, politics, industry, research and the public sector must meet these challenges. I am convinced that with teamwork the energy turnaround will be successful.

The decision to phase-out nuclear energy requires the courage to change. Effecting the transition, indeed, presents a unique chance for Germany to place itself in a leading position worldwide and serve as a source of inspiration for the energy turnaround. We must press ahead quickly with expanding and restructuring the grid, finding storage solutions and establishing decentralised and regional energy systems. As the largest solar energy research center in Europe, Fraunhofer ISE will engage all its energy and motivation to make the energy turnaround a reality in Germany and beyond – moving

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away from fossil fuel and towards renewable energy systems. Together with other Fraunhofer Institutes, for example in the Fraunhofer Energy Alliance, our aim is to provide affordable solutions for the energy transformation and to make energy storage commercially viable. We are working in full swing to continually develop even more efficient technologies for photovoltaic and thermal solar systems and power plants. In the following, I would like to mention some of the selected highlights from our Institute which took place in 2011.

With and for our partners from business, industry and politics, we published several studies in 2011 with groundbreaking results on the regional and international level. One of these studies, "Energieentwicklungspfad für Baden-Württemberg" (Future energy development path for Baden-Wuerttemberg) outlined the possibilities for transforming the energy system in Baden-Wuerttemberg. With the present political situation, we are more optimistic than ever that the strategies outlined in the study can be put into practice today. In a further study for the World Bank, Fraunhofer ISE and Fraunhofer ISI worked on a study to investigate the energy political and economic potential of solar thermal power plants in the MENA region (see page 56).

Again in 2011, we participated in many scientific conferences throughout the world and contributed on a large scale towards successful further developments in the field of renewable energy. The SiliconPV – International Conference on Silicon Photovoltaics celebrated its premiere in 2011. 450 scientists from 17 countries participated in the first conference of its kind. In April 2012, this conference series will continue, taking place in Leuven, Belgium.

In 2011, the Solar Summit Freiburg was held for the fourth time. In addition to presenting an overview on the most recent developments of important solar technologies, the 2011 conference focused on organic photovoltaics. The next Solar Summit Freiburg will take place in October 2012.

Again in 2011, the scientific results from our researchers were distinguished with many prizes and honours:

Dr Herbert Schmidt received the Joseph von Fraunhofer Prize for developing the HERIC® topology for inverters. With this technology, the losses during the conversion of direct to alternating current for grid feed-in are cut in half, leading to an inverter world record of over 99 per cent in 2009. This technology has been implemented in solar inverters many times over (Fig. 1). Together with Fraunhofer researchers and colleagues from the Carnot Institute, Dr Frank Dimroth was awarded the Franco-German Business Award 2011. They were honoured for their work on reuseable substrates for the III-V multi-junction solar cells. For their work on concentrator photovoltaics with highest efficiency solar cells, Dr Andreas Bett (Fraunhofer ISE), Hansjörg Lerchenmüller (SOITEC) and Dr Klaus-Dieter Rasch (AZUR SPACE) were among the finalists for the German Future Prize 2011. One distinction, which I am personally, and in the name of our institute, very pleased to receive, is from the magazine "WirtschaftsWoche". I was named the most important researcher of the energy turnaround. In our anniversary year, Fraunhofer ISE also received a prize and was designated for the second time as "Ausgewählter Ort 2011" (Selected Site 2011) in the innovation competition "Deutschland – Land der Ideen" (Germany – Country of Ideas).

2

On the occasion of our 30th anniversary, we named the following long-standing employees as fellows of Fraunhofer ISE: Dr Andreas Hinsch, Dr Michael Köhl, Prof Dr Roland Schindler, Dr Heribert Schmidt, Prof Dr Gerhard Willeke and Dr Helen Rose Wilson. As internal scientific consultants, they will serve an advisory function for future developments at Fraunhofer ISE. Dr Florian Clement, Dr Stefan Henninger, Sebastian Herkel, Felix Jeremias, Florian Kagerer and Dr Peter Schossig received the 2011 Benefits for Excellence from the Fraunhofer-Gesellschaft.

In 2011, the following structural changes for the future have been enacted at Fraunhofer ISE:

An eighth business area has been added to the previous seven. The new business area is called Photovoltaic Modules and Systems and is led by Dr Harry Wirth (see page 82). With his team he has continually built up and expanded this topic at Fraunhofer ISE over the years. At Fraunhofer CSP in Halle, jointly operated by Fraunhofer ISE and Fraunhofer IWM, Dr Peter Dold has taken on the leadership of the Laboratory for Crystallisation Technology (CSP-LKT) (see page 12). Two colleagues from the business area of Energy-Efficient Buildings were offered professorships: Dr Jens Pfafferott in the area of Energy Efficiency in Industrial Media Supply at the University of Applied Sciences, Offenburg and Sebastian Herkel in the area of Climate Engineering at the University of Technology in Stuttgart. To our delight, Sebastian Herkel will continue to work at Fraunhofer ISE.

1 *Dr Heribert Schmidt awarded the Joseph von Fraunhofer Prize 2011 for developing the HERIC® topology for inverters.*
2 *Dr Andreas Bett (Fraunhofer ISE), Hansjörg Lerchenmüller (SOITEC), Dr Klaus-Dieter Rasch (AZUR SPACE) nominated for the German Future Prize 2011 for their work on concentrator photovoltaics with highest efficiency solar cells.*

With its research facilities and results, an operating budget of 61.3 million euro and a staff of 1139, Fraunhofer ISE today holds a stronger position than ever before. The global photovoltaic market is growing at 40-60 per cent annually, and of all the renewable energies, photovoltaics has experienced the fastest cost reduction. In the past seven years, the price for solar electricity has dropped by half. In spite of repeated criticism in politics and in the media, I am convinced that Germany has the innovative research capability and the perseverance to master the transition to a green energy system with the help of photovoltaics and other renewable energy systems. We are aware of this new dimension and singular chance. In 2012, we continue to commit ourselves with one hundred per cent towards one hundred per cent renewable energy.

To conclude, I would like to sincerely thank all of those who have continually encouraged and supported us over the past thirty years: our Board of Trustees and grant sponsoring organisations, our contact persons in the ministries on the federal and state levels as well as the staff of the relevant project management organisations, especially in the industry.

TABLE OF CONTENTS

TABLE OF CONTENTS

82 PHOTOVOLTAIC MODULES AND SYSTEMS

92 ALTERNATIVE PHOTOVOLTAIC TECHNOLOGIES

104 RENEWABLE POWER SUPPLY

118 HYDROGEN TECHNOLOGY

130 SERVICE UNITS

143 APPENDIX

1

2

ORGANISATIONAL STRUCTURE

The Fraunhofer Institute for Solar Energy Systems ISE is organised in two parallel structural forms that are mutually compatible: the business areas and the scientific divisions. The external presentation of our Institute, our marketing activities on R&D, and above all, our strategic planning are structured according to the eight business areas which reflect the main research topics addressed by the Institute. The scientific divisions of the Institute are responsible for the research and development (R&D) in the laboratories, project work and the concrete organisation of work. Most of the scientific and technical staff are assigned to work in one of these eight divisions.

Fraunhofer ISE is supported by long-standing mentors and experts in the solar energy branch: Prof Dr Adolf Goetzberger (Founder of the Institute and Institute Director 1981–1993), Prof Dr Joachim Luther (Institute Director 1993–2006; presently Director of the Solar Energy Research Institute of Singapore SERIS), Prof Dr Volker Wittwer (Deputy Institute Director 1997–2009) and Dr Claus Beneking (former CEO ErSol Solar Energy AG).

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	Dr Hans-Martin Henning	+49 761 4588-5134
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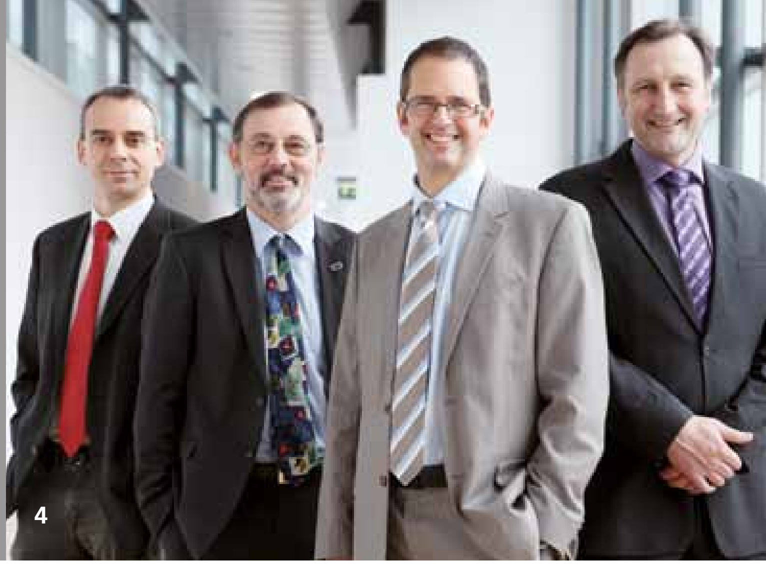


1 The directors of Fraunhofer ISE (f.l.t.r.): Dr Holger Schroeter, Chief Financial Officer; Dr Hans-Martin Henning, Deputy Director and Division Director "Thermal Systems and Buildings"; Prof Dr Eicke R. Weber, Institute Director; Dr Andreas Bett, Deputy Director and Division Director "Materials – Solar Cells and Technologies".

2 Karin Schneider, Head of "Press and Public Relations".

3 / 4 Directors of the scientific divisions at Fraunhofer ISE (f.l.t.r.): Dr Werner Platzer "Solar Thermal and Optics", Dr Günther Ebert "Electrical Energy Systems", Dr Christopher Hebling "Energy Technology", Dr Hans-Martin Henning "Thermal Systems and Buildings", Dr Harry Wirth "Photovoltaic Modules, Systems and Reliability", Dr Andreas Bett "Materials – Solar Cells and Technologies", Dr Ralf Preu "PV Production Technology and Quality Assurance", Dr Stefan Glunz "Solar Cells – Development and Characterisation".

SCIENTIFIC DIVISIONS

Thermal Systems and Buildings	Dr Hans-Martin Henning	+49 761 4588-5134
Solar Thermal and Optics	Dr Werner Platzer	+49 761 4588-5983
Materials – Solar Cells and Technologies	Dr Andreas Bett	+49 761 4588-5257
Solar Cells – Development and Characterisation	Dr Stefan Glunz	+49 761 4588-5191
PV Production Technology and Quality Assurance	Dr Ralf Preu	+49 761 4588-5260
Photovoltaic Modules, Systems and Reliability	Dr Harry Wirth	+49 761 4588-5858
Electrical Energy Systems	Dr Günther Ebert	+49 761 4588-5229
Energy Technology	Dr Christopher Hebling	+49 761 4588-5195

THE INSTITUTE IN BRIEF

The Fraunhofer Institute for Solar Energy Systems ISE is committed to promoting energy supply systems which are sustainable, economic, safe and socially just. It creates technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialised, threshold and developing countries. To this purpose, the Institute develops materials, components, systems and processes for the following business areas: energy-efficient buildings, applied optics and functional surfaces, solar thermal technology, silicon photovoltaics, photovoltaic modules and systems, alternative photovoltaic technologies, renewable power supply and hydrogen technology. With activities extending well beyond fundamental scientific research, the Institute is engaged in the development of production technology and prototypes, the construction of demonstration systems and the operation of testing centres. The Institute plans, advises, tests and provides know-how and technical facilities as services. Fraunhofer ISE has been certified according to DIN EN ISO 9001:2000 since March, 2001.

Research and Services Spectrum

The Fraunhofer Institute for Solar Energy Systems ISE is a member of the Fraunhofer-Gesellschaft, a non-profit organisation, which occupies a mediating position between the fundamental research of universities and industrial practice. It conducts applications-oriented research to benefit the economy and society at large. Fraunhofer ISE finances itself to more than 90 percent with contracts for applied research, development and high-technology services. The working method is characterised by its clear relevance to practice and orientation toward the wishes of the client. The Institute is integrated into a network of national and international co-operation. Among others, it is a member of the ForschungsVerbund Erneuerbare Energien (FVEE – German Research Association for Renewable Energy) and the European Renewable Energy Centres (EUREC) Agency. The Institute can draw on expertise from other Fraunhofer Institutes, so that complete interdisciplinary solutions can be offered.

Networking within the Fraunhofer-Gesellschaft

- member of the Fraunhofer Alliances for "Building Innovation", "Energy", "Nanotechnology", "Optic Surfaces", "Photocatalysis" and "Water Systems" (SysWater)
- member of the Fraunhofer Electromobility Systems Research project
- member of the Fraunhofer Group "Materials, Components" (materials research)

International Clients and Co-operation Partners

The Fraunhofer Institute for Solar Energy Systems ISE has co-operated successfully for years with international partners and clients from a wide range of business sectors. A list of our national and international partners can be found under www.ise.fraunhofer.de/about-us/our-partners.

External Branches and Co-operations

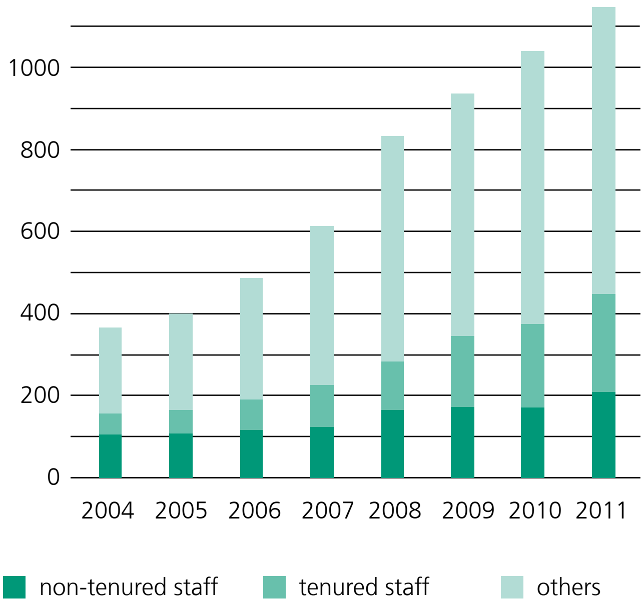
The Fraunhofer ISE Laboratory and Service Centre LSC in Gelsenkirchen, in the State of North Rhine-Westphalia (NRW), serves as a partner for the photovoltaic industry also beyond the borders of NRW. Solar cell manufacturers draw on the services of LSC for quality control of their production and for rapid solutions to problems in their processing lines. The services offered by the Laboratory include the simulation and optimisation of in-line processes, the development of new processes and structures for solar cells as well as research on large-area heterojunction solar cells of amorphous and crystalline silicon. LSC Gelsenkirchen also offers training sessions on characterisation procedures and solar cell technology (see page 65).

The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle/Saale was jointly founded by the Fraunhofer Institute for Mechanics of Materials IWM, Freiburg and Halle, and the Fraunhofer ISE. Fraunhofer IWM contributes its expertise in the area of optimisation and evaluating silicon process technologies and module integration. Fraunhofer ISE's competence lies in the manufacture of materials, solar cell and module development as well as characterisation. The central facilities are presently Reliability and Technologies for Grid Parity (CSP-ZTN) and the Laboratory for Crystallisation Technology (CSP-LKT) (see page 12).

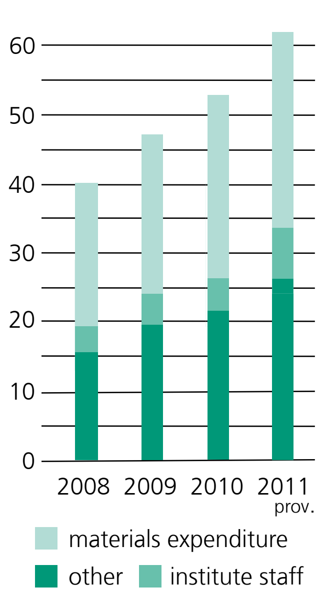
The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, is a co-operation between Fraunhofer ISE and the Fraunhofer Institute for Integrated Systems and Device Technology IISB in Erlangen. THM supports companies through research and development on materials preparation and processing of 300 mm silicon, solar silicon and III-V semiconductors. Beyond this, THM offers services in the fields of analytics, characterisation and testing to assist industry partners in their ongoing production.

The Fraunhofer Center for Sustainable Energy Systems CSE in Boston contributes to further adapt and introduce the expertise and technology in the field of renewable energy established in Europe to the United States market. Together with the Canadian Standards Association (CSA) and the VDE Institute for Testing and Certification, the Fraunhofer CSE set up a test facility for PV modules in 2010. The facility, called the CFV Solar Test Laboratory, is located in Albuquerque, New Mexico.

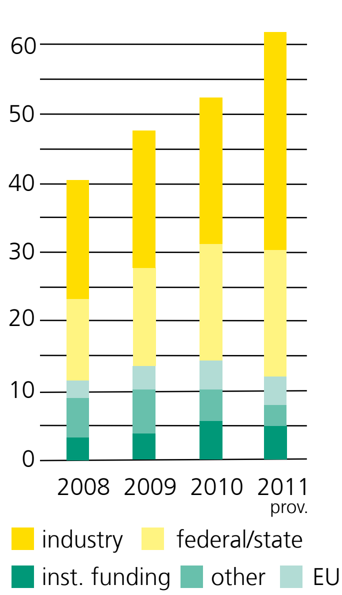
Personnel



Expenditure million euros



Income million euros



On 31 December 2011, a total of 1139 staff members were employed at Fraunhofer ISE. Included in this total are 151 doctoral candidates, 102 diploma/masters students, 52 trainees, 11 apprentices and 282 scientific assistants as well as 113 further staff (e.g., guest scientists) who support the research projects with their work and thus contribute significantly to the scientific results obtained. In this way, Fraunhofer ISE makes an important contribution towards educating researchers in this significant field of work.

The financial structure of the Fraunhofer-Gesellschaft distinguishes between the operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. In 2011 our operational totalled 61.3 million euro. In addition to the expenditure documented in the graph, the Institute made investments of 7.7 million euro in 2011 (not including investments for building construction and the economic stimulus programme).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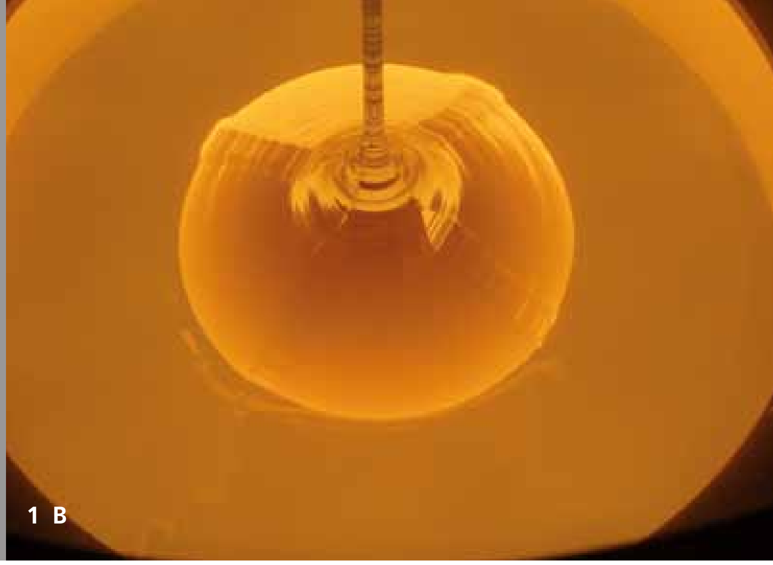
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FRAUNHOFER CSP: LABORATORY FOR CRYSTALLISATION TECHNOLOGY

The Fraunhofer Center for Silicon Photovoltaics CSP is located in Halle and is managed jointly by Fraunhofer ISE and Fraunhofer IWM. The laboratory for crystallisation technology LKT at Fraunhofer CSP has the most modern equipment for crystallisation of silicon for photovoltaics at hand. In industrial facilities, we produce monocrystalline ingots using both Czochralski and Float-Zone processes as well as multicrystalline blocks using the Vertical Gradient Freeze method. We address questions on crucible life-time, feedstock material quality, and we carry out analyses on residual contamination. For the development of photovoltaics in the coming years, we attach particular importance to increasing the efficiency through the establishment of n-type silicon and developing quasi-monocrystalline blocks.

Rainer Barth, Roland Kunert, Joachim Prause, Stefan Wieczorek, Heiko Wust, **Peter Dold**

Work at the Fraunhofer Centre for Silicon Photovoltaics CSP is divided into two divisions, "Reliability and Technology for Grid Parity" (CSP-ZTN) led by Prof Dr Jörg Bagdahn assigned organisationally to Fraunhofer IWM, and the "Laboratory for Crystallisation Technology" (CSP-LKT). Under the leadership of Dr Peter Dold and in close co-operation with Fraunhofer ISE, CSP-LKT performs research on the further development of crystallisation technologies for photovoltaics.

In CSP-LKT, we are working on the three most important crystallisation technologies to grow silicon crystals for photovoltaics. We are concentrating on the Czochralski (Cz) and the float-zone (FZ) processes to produce monocrystalline ingots.

Modern industrial equipment (EKZ 2700) from the company PVA Tepla is available to us for further development of the Cz process. With this equipment we can produce Cz ingots with a mass of ca. 60 kg, a diameter of ca. 205 mm (8") and a length of ca. 60 cm. The enlargement to a diameter of 9" is in process and will allow us to provide full-square monocrystalline wafers. The research work in Cz crystallisation focuses on the interaction between the silicon melt and the crucible, the incorporation and transport of oxygen into the crystal, process optimisation and processing time reduction. Analysing the feedstock material from different manufacturers is another important theme, in particular for the processing of UMG silicon for the crystallisation of monocrystalline ingots. Additionally, we offer the manufacturing of customer specific crystals, customised according to our clients' specifications with respect to doping, diameter or processing parameters.

Growing crystals according to the Float-Zone procedure results in single crystals with the best material quality, from which solar cells with the highest efficiency can be produced. However, the material is not significantly represented on the PV market due to the high production costs at present. The

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research work at CSP-LKT is aiming for a reduction of the specific production costs for FZ material. To this end, we are pursuing approaches with industrial partners which allow the process to be more fully automated. Beyond that, we are investigating new feedstock materials which were developed by external partners especially for photovoltaic applications. For the experiments, we produce test crystals with 4” diameter and variable length in a laboratory facility (Model FZ-14).

The third crystallisation technology which we have is the Vertical Gradient Freeze (VGF) process. We use industrial equipment from PVA Tepla (BGF-732 multicrystalliser) with which multicrystalline blocks of G4 can be produced. At present, our work concentrates on quasi-mono (also mono-like or mono-cast) materials. What is the potential of these processes for increasing efficiency without increasing costs? The answer to this question lies in clarifying the maximum reusability of the priming plate, minimising the defect density through suitable engineering and optimising the heating or cooling phases. The work is being carried out in close co-operation with the on-going research work at Fraunhofer ISE on VGF processes for smaller ingots of G1/G2.

By integrating a residual gas analyser in the crystallisation process, we are able to investigate the release and removal of volatile by-products and contaminants (such as H_20, CO or also sulphur, chlorine or nitrogen compounds) as a function of the process parameters. The further processing and analysis of all crystals produced are carried out co-operatively between CSP-ZTN and Fraunhofer ISE.

1 *Production of monocrystalline silicon according to the Czochralski process (Cz), with illustrations of the crucible filled with feedstock (A), the nucleation phase (B) and the final crystal (C).*
2 *Production of monocrystalline silicon by the Float-Zone (FZ) process; Melting zone during processing (A) and FZ final crystal, ready to be taken out of the furnace (B).*

The work is supported by the German Federal Ministry of Education and Research (BMBF) within the framework of the “Solarvalley Mitteldeutschland” Cluster of Excellence.

RENEWABLE ENERGY INNOVATION POLICY

The partnership of the Fraunhofer Center for Renewable Energy Innovation Policy (RENIP) combines the competences of the Fraunhofer Institute for Solar Energy Systems ISE and the Fraunhofer Institute for Systems and Innovation Research ISI. With this synergy, the increasing need for a close co-operation of technology development and applied research with economic systems analysis and innovation research is met. RENIP offers a new type of service whereby the energy market potential of the technology is analysed and successfully guided from the start. As a result, especially efficient and goal-oriented research and support services are available to customers from industry and the public sector.

Creating a sustainable and secure energy system presents a huge challenge equally for industry, society and politics. With the development and market positioning of new technologies, however, a real chance exists to strengthen the economic competitiveness of the German and European industry. This requires, in addition to further technological breakthroughs, the development of suitable economic strategies for the research, demonstration and market diffusion of new innovations.

In the study, "Stromgestehungskosten von Erneuerbaren Energien" (Electricity Production Costs of Renewable Energies), an assessment was made of the different renewable energy technologies using a good basis of comparison. In the further analysis, RENIP does not limit itself to Germany, but rather includes other European and Mediterranean countries such as Egypt, Jordan, Morocco and Turkey.

For the World Bank, RENIP worked on a study entitled "MENA, Assessment of Local Manufacturing Potential for Concentrated Solar Power (CSP) Projects" (see page 56). This study is now used as the standard work in investigating the local value added by renewable energy technologies. The potential of the whole value chain is considered – from the planning of a new solar power plant, its construction through to the production of the components. A detailed plan of action is developed to maximise the energy political and economic potential. Building on this work, RENIP cooperates with individual MENA countries and industry to realise technical solutions for solar energy technologies. Further, suitable market entry strategies are developed as well as the technical and market integration.

In addition to carrying out fundamental work on the set-up and integration of renewable energy technologies in the electrical power market, RENIP also carries out investigations on political measures aimed at increasing building renovation.

RENIP offers

- country-specific analysis of renewable energies using computer modelling and economical evaluations
- investigations on the market potential and industry potential of solar energy technologies
- development of implementation strategies and determination of political boundary conditions

BOARD OF TRUSTEES

The Board of Trustees assesses the research projects and advises the Institute Directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the work programme of Fraunhofer ISE (Status: 24 October 2011).

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CELEBRATING 30 YEARS OF SOLAR RESEARCH

In 2011 the Fraunhofer Institute for Solar Energy Systems ISE celebrated its 30th anniversary. What began as a vision of Professor Adolf Goetzberger, the Institute's founder, has long become a reality. Founded on 1 July 1981 in Freiburg with around 20 pioneers of solar research, Fraunhofer ISE today has developed into the largest solar research institute in Europe with over 1100 employees and the second largest institute of the Fraunhofer-Gesellschaft. The Institute celebrated its historical success story with a festive gala and open house in July 2011.

With the founding of Fraunhofer ISE in 1981, Prof Dr Adolf Goetzberger also established the basis for photovoltaic research. The ambitious goal "to move away from fossil fuels and nuclear energy sources and to replace them with renewable energy sources" was often made spot of back then during the "solar ice age", the term coined by the keynote speaker Dr Knut Kübler, Assistant Head in the Federal Ministry for Finance and Technology to describe the period in which the Institute was founded. In the following years during the so-called "solar transitional period", the Institute was brought onto a successful economic course under the direction of Prof Dr Joachim Luther. At present, the Institute finds itself in the "hot solar period" under the leadership of Prof Dr Eicke R. Weber.

In its 30 year history, Fraunhofer ISE has brought forth many scientific highlights: the first energy autonomous solar house in 1992, the world record for multicrystalline silicon solar cells at over 20.3 per cent in 2004, the first solar cooling installed in 2001 and the world record for inverter efficiency at 99.03 per cent as well as the world record for the concentrator solar cells at 41.1 per cent both established in 2009. In the same year, Prof Adolf Goetzberger was honoured as "Inventor of the Year" for his lifework by the European Patent Office.

1 *About 400 invited guests attended the 30th anniversary celebration of Fraunhofer ISE.*

2 *At the 30th anniversary celebration, fire dancers let the sparks fly.*

The success record is also seen in the amount of Fraunhofer ISE spin-off companies – presently numbering more than a dozen. The most successful example to date is the Freiburg company SOITEC Solar – formerly Concentrix Solar. The former spin-off of Fraunhofer ISE is today world market leader in producing concentrator modules.

In research, industry and politics, Fraunhofer ISE has become a driving force. Today the Institute is one of the most important pace setters and research partners worldwide towards the goal of 100 per cent renewable energy.

To celebrate this positive balance, around 400 invited guests from the research, finance and politics came to Freiburg to attend a festive gala. At our Open House in the same week, Fraunhofer ISE was open to the public and approximately 1000 public guests interested in solar energy research attended. On this note, let us say "To another successful 30 years!"

AWARDS AND PRIZES

Dr Heribert Schmidt was a recipient of the Joseph von Fraunhofer Prize 2011. At the Fraunhofer Annual Meeting on 26th May 2011 in Nuremberg, he was honoured for the development of the HERIC® topology for inverters. With this technology, the losses incurred when converting the solar power from direct to alternating current are cut in half. This led to a world record inverter efficiency of over 99 % in 2009.

1 *A recipient of the Joseph von Fraunhofer Prize 2011: Dr Heribert Schmidt (third from right, 1st row) He was honoured for the development of the HERIC® topology for inverters.*

Dr Stefan Lindekugel with his colleagues received the Poster Award of the 26th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC). The award was presented at the PVSEC (5–9 Sep. 2011) in Hamburg. The poster topic was on solid phase crystallization and rapid thermal annealing processes for crystalline silicon on glass in a movable two-sided halogen lamp oven.

The SolarWorld Junior Einstein-Award went to **Dr Paul Gundel** (alumnus) for his concept on the development of new microscopic measurement methods for characterising solar cells. This prize was also bestowed on 5 Sep. 2011 at the PVSEC in Hamburg.

Dr Wolfgang Guter (alumnus) was awarded 2nd place of the "Deutsche Studienpreis 2011" from the Körber Stiftung. He was honoured for his doctoral dissertation on the optimisation of III-V based highly efficient solar cells. The award ceremony took place on 8 Nov. 2011 at the Deutsche Parlamentarische Gesellschaft in Berlin.

For his diploma work, **Kurt-Ulrich Ritzau** received the "Nachhaltigkeitspreis" (Sustainability Award) from the University of Tübingen. The prize was bestowed on 11 Nov. 2011 in Tübingen. The topic of the work was the manufacture, analysis and optimisation of a silicon hetero-junction solar cell with multicrystalline absorber.

Dr Frank Dimroth, together with Fraunhofer researchers and colleagues from the Carnot Institute "Laboratoire d'électronique des technologies de l'information CEA-LETI", received the Franco-German Business Award 2011. On 5 Dec. 2011 in Paris, they were honoured collectively for their work on "Reuseable substrates for III-V multi-junction solar cells".

Dr Andreas Bett, Hansjörg Lerchenmüller (SOITEC), Dr Klaus-Dieter Rasch (AZUR SPACE) were among the finalists for the German Future Prize 2011 (Deutsche Zukunftspreis 2011). They were nominated for their work on concentrator photovoltaics with highest efficiency solar cells.

R&D HIGHLIGHTS

ENERGY-EFFICIENT BUILDINGS

- cold storage based on phase change slurries first implemented on a technical scale (5 m^3)
- energy concept realized for the first residential high-rise worldwide renovated to passive house standards (Freiburg-Weingarten, Bugginger Str. 50)
- synthesis of metal-organic framework materials reached a world record water uptake capacity (1.4 g water per gram material)

APPLIED OPTICS AND FUNCTIONAL SURFACES

- successful structuring of etching masks using roller nano-imprint for honeycomb texturing of multicrystalline silicon solar substrates with dimensions 156 x 156 mm^2
- manufacture of diffractive back side grid in silicon by means of interference lithography, nano-imprint and plasma etching as well as determining the increase in absorption due to these photonic structures
- development of selective absorbers on high-alloyed steels
- Fresnel lens with improved temperature behaviour for the concentrator photovoltaics

SOLAR THERMAL TECHNOLOGY

- demonstration system consisting of newly developed solar collectors with static reflectors put into operation for generating process heat for a laundry
- as compared to PVT collectors available on the market, significant improvements achieved through the direct lamination of c-Si cells on aluminium roll-bond absorbers with fractal channel structures
- feasibility of an innovative latent storage concept (for steam cycle) with screw heat exchanger to decouple the heat exchanger surface from the storage capacity
- further optimisation of concentrator systems (field of Scheffler dishes or heliostats for solar thermal towers) by means of ray tracing

SILICON PHOTOVOLTAICS

- in situ doping for Vertical Gradient Freeze (VGF) method
- silicon solar cells with copper metallisation show high efficiencies (>21%) and very good long-term stability
- laser-chemical processing successfully implemented for local boron doping
- n-type solar cell with an ion-implanted boron emitter achieves efficiency of 21.7 %
- fully implanted back-side contacted solar cell with an efficiency of 20 %

- TCO-free hetero-junction solar cell with diffused front-side and back-side collecting amorphous silicon emitter with efficiency of 21.2 %
- quasi-static photoluminescence method available for reliable lifetime measurements of silicon with unknown doping and mobility
- local concentrations of frequently occurring impurities in silicon (iron, chromium, boron/oxygen) can be identified with imaging luminescence
- large area solar cells with laser-doped selective emitter, printed contacts and laser fired back side contacts manufactured with an efficiency of 20 %
- MWT-PERC solar cell on large-area boron-doped mono-crystalline, or multicrystalline, silicon layer manufactured in PV-TEC with an efficiency of 20.6 %, or 18.3 %, respectively

PHOTOVOLTAIC MODULES AND SYSTEMS

- TopMod: efficient module technology developed to minimize efficiency losses; solar module constructed using 60 commercial silicon solar cells with nominal cell efficiency of 16.0 %. Module efficiency reaches 15.2 % with respect to the total module area, thus loss of only 5 % relative to the initial cell efficiency.

ALTERNATIVE PHOTOVOLTAIC TECHNOLOGIES

- 32 % efficiency achieved for the FLATCON® test module
- manufacture of the first worldwide dye solar module with an area 60 cm x 100 cm

RENEWABLE POWER SUPPLY

- PV reverse osmosis plant installed and put into operation on Cyprus
- IBS66 battery system for electric vehicles constructed and demonstrated successfully with charging station and ECM technology
- SmartEnergyLab successfully set up; investigations on grid integration are available at a level near to the practice in the areas of PV, CHP and electric mobility
- highly efficient bi-directional fast charging station (power output of 22 kW) developed for electric vehicles

HYDROGEN TECHNOLOGY

- 50 kW diesel reformer delivered to the company MTU Friedrichshafen for investigations on diesel particle filter regeneration by synthesis gas
- 100 W PEM fuel cell systems with cold start capability for emergency medical services
- outdoor installation of four test stands to record the long-term degradation effects of PEM fuel cells due to air pollution

BUILDING EFFICIENTLY WITH THE SUN

ENERGY-EFFICIENT BUILDINGS

Buildings today are energy consumers. Creating a pleasant indoor climate, providing lighting and using the building all lead to a demand – which varies in magnitude according to the building standard – for electricity and other forms of energy, most commonly fossil fuels. In the future, buildings may become net energy suppliers, if renewable energy sources are used locally and excess energy is fed into the electricity grid. In buildings with a very high energy standard and correspondingly low consumption, a positive balance can be achieved for the annual average. Although buildings of this type are already in operation today, there are still only a few isolated pilot objects.

However, the European Parliament has drafted a law which proposes that new public buildings after 2019 and all new buildings after 2021 will be required to meet a zero-energy standard – in other words, they must demonstrate a neutral or positive energy balance in the annual average. Currently, the zero-energy approach is becoming established as the new guiding principle to evaluate buildings. Regardless of how the standard is achieved for specific cases, the use of solar energy will play a central role. Solar thermal systems help to reduce the remaining energy demand significantly for domestic hot water and space heating, and also for cooling if required, and photovoltaic systems can not only contribute to meeting the electricity demand but also feed excess solar energy in the form of electricity into the grid. One major challenge for the future is to enable much greater integration of the solar systems into the building and the building envelope, without affecting structural requirements and the lifetime of building systems negatively. In particular, corresponding concepts must also be developed for the existing building stock and be applied on a widespread basis. It is also important to develop concepts which minimise the negative impact on electricity grids. The significance of this topic will grow further in future, when an increasing share of fluctuating energy from renewable sources such as the sun and wind contributes to the electricity supply. Work on developing appropriate concepts for operation management and control thus has a high priority, as does the development of new storage technology, which makes a larger proportion of local load management feasible.

At Fraunhofer ISE, buildings and their technical equipment represent a central field of work. Our comprehensive knowledge of technology to use solar energy, on the one hand, and our long years of experience in R&D activities for energy-efficient buildings, on the other, allow us to develop optimal solutions for the zero-energy buildings sketched above. In the same way as we assist manufacturers in the development of new components and energy supply technology, we also support planners and architects in designing high-quality buildings. We address the topics over a broad scope, ranging from fundamental development, e.g. of materials or coating technology, to market introduction of components and systems. For implementation in building projects, we offer planning, consultancy and concept development on all issues concerning energy and user comfort. In doing so, we apply the most advanced simulation modules, which we develop further if necessary. Practical implementation of quality control plays an important role, which we achieve by accompanying and analysing demonstration buildings and urban quarters, and also by carrying out comprehensive field tests and monitoring campaigns.

Classic topics of our work on the building envelope are the use of daylight and solar shading. In addition, the integration of active components into the building envelope, including solar energy converters such as photovoltaic modules or solar thermal collectors, is becoming increasingly important. The thermal storage capacity of building systems plays an important role in implementing energy-saving cooling concepts. Processes and systems based on phase-change materials for lightweight buildings continue to be significant here, as do thermally activated building systems.

Efficient conversion technology plays a central role in heating buildings. Both electric and gas-fuelled heat pumps form a basis for promising concepts, particularly for energy-efficient buildings which can be heated with low-temperature systems. Thermal solar energy can be used not only for heating of domestic hot water and solar-assisted space heating but also for air-conditioning in summer, an application which is particularly attractive for sunny regions with a high cooling demand. Architecturally appealing integration of photovoltaics into the building envelope is a central task to encourage widespread adoption and good acceptance.

Operation management is essential for optimal functioning of complete systems, consisting of the building envelope, HVAC technology and the users. New, model-based concepts for operation management are used to constantly monitor and evaluate, and if necessary adjust, the performance of individual building components. Such measures, which are implemented at relatively low investment cost, can achieve significant savings in energy consumption and operating costs. Both the development and also the implementation of corresponding procedures for energy-efficient operation management and control thus represent important fields of our work.

In collaboration with architects, professional planners and industrial companies, we develop concepts for the buildings of tomorrow. We follow an integrated planning approach, optimising concepts with respect to economic viability, energy efficiency and user comfort. Particularly in built-up areas, energy concepts which address not just individual buildings but whole urban quarters are gaining increasing importance, particularly when grid solutions are addressed. We have extended the scope of our activities accordingly. Our efforts to define the international boundary conditions for this work include our participation in programmes of the International Energy Agency IEA.

In future, multi-functional façades will play an important role for the energy-saving renovation of buildings. The façade will integrate more functions than just the classic ones of weather protection and thermal insulation, so that constructional changes to the building interior can be avoided. Pre-fabricated systems which can be installed easily should be used for economic reasons. As part of a project which was supported by the German Federal Ministry of Economics and Technology (BMWi), we have developed façade insulation panels with integrated inlet and outlet air ducts to ensure hygienically necessary air exchange, combined with heat recovery. Not only the thermal insulation panels with their integrated air ducts but also the window elements are highly pre-fabricated and include the interfaces to the façade and thermal insulation. A prototype system was installed on an existing building at Fraunhofer ISE by our industrial partners, Beck & Heun and Zehnder.

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NEW ENERGY CONCEPT FOR A SUPERMARKET

About 7 million CO_2-equivalent tonnes are emitted annually in Germany from the refrigeration units of food retailers. This emission consists of both direct emission due to refrigerant leaks and indirect emission caused by energy consumption. If the effects of refrigeration, lighting and other types of electricity consumption are totalled, more than 1 % of German greenhouse gas emission is due to the food retail sector. The combination of various types of technology for building services, daylighting and the application of natural refrigerants such as CO_2 with a low greenhouse potential can significantly improve the environmental footprint of supermarkets.

Sebastian Burhenne, Doreen Kalz, **Nicolas Réhault**, Hans-Martin Henning

1 *The new ALDI SÜD supermarket in Rastatt.*

2 *Interior view of the supermarket. The skylights with their microscopic gratings and the display refrigeration units, which are cooled with a CO_2-based system, are visible.*

In collaboration with the building owner and the planning team, Fraunhofer ISE prepared a novel energy concept for the new ALDI SÜD supermarket in Rastatt. The aim of the energy concept was to reduce the primary energy demand of this supermarket by 50 % compared to the standard version by an integrated combination of numerous individual measures concerning the generation of cooling power, refrigerated units, the building envelope and technical building services. Energy efficiency in supermarkets is achieved primarily by efficient commercial refrigeration and by utilising the potential for heat recovery and use of waste heat. Both the refrigeration methods and the refrigeration equipment for the new supermarket were selected and further developed according to energy-relevant criteria. In addition, skylights with a highly reflective microscopic grating in the space between the panes of the low-e coated triple glazing were installed. These ensure good visual contact and solar control simultaneously. For the artificial lighting, not only have highly efficient luminaires been installed but daylight-dependent control has been implemented.

The core of the concept is a geothermally assisted, CO_2-based refrigeration network, which meets all energy demands for heating and cooling by consistent utilisation of waste heat from the refrigeration plant and free cooling from the borehole heat exchanger. As a result, there was no need for the other equipment which is usually installed, such as a gas-fuelled boiler for heating or an air-conditioning unit to cool the supermarket. One weakness of CO_2 cooling systems is that the coefficient of performance drops markedly during periods of high outdoor temperatures if the gas cooler is cooled by outdoor air. In this project, this effect is reduced by combination with a borehole system to cool down the refrigerant.

The two-year monitoring phase started soon after the supermarket was opened in October 2010. The data to determine energy balances and to optimise operation are acquired and analysed continuously. Optimisation potential for controlling the CO_2 refrigeration unit, which had been newly developed by the Hafner-Muschler company, was identified and implemented. The daylight-dependent control of the artificial lighting was also continually improved with regard to energy efficiency and optimal visual comfort. Further optimisation is planned for the second year of monitoring.

This project was supported by the German Federal Ministry of Economics and Technology (BMWi).

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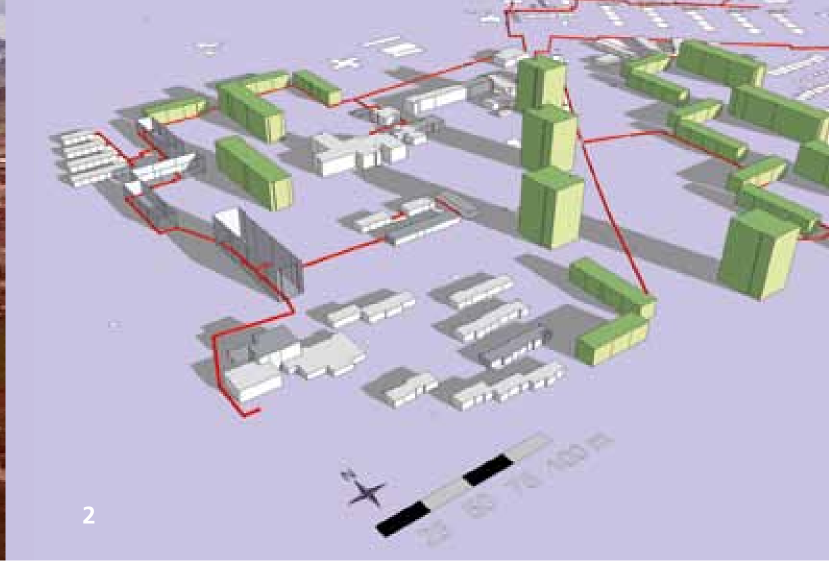

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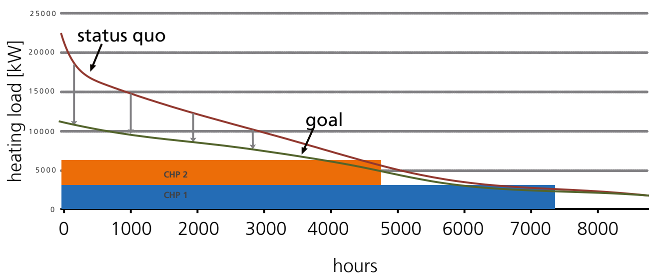
MODEL RENOVATION OF THE SUBURB OF WEINGARTEN-WEST IN FREIBURG

Energy-related renovation will be carried out in the suburb of Weingarten-West from 2007 until about 2022. The accompanying research project has the goals of planning, implementing, monitoring and analysing the energy-relevant aspects of building renovation and the energy supply for this suburb. The primary energy consumption for all energy services is to be reduced by 30 %. In the project, renovation concepts will be developed for typical buildings from the 1960's and the resulting changes in the heating supply structure will be investigated. The total heating energy demand for the suburb will decrease due to the improved standard of the buildings. In particular, this affects the supply of district heating from a combined heat and power (CHP) station. We will also investigate how operation of the district heating system can be adapted to the changed demand.

1 Historical photo of the Weingarten West suburb.

2 3D representation of the suburb and the district heating network.



3 Total cumulative heating load distribution for the district heating supply: The reduction in the heating demand particularly affects operation of the CHP (combined heat and power) plant.

Sebastian Herkel, **Florian Kagerer, Sattaya Narmsara**, Hans-Martin Henning

The effects of the decreasing heat demand on the heating supply structure will be analysed dynamically on the basis of simulations. To this purpose, an interface was developed which links the topology of the district heating network recorded in the energy utility's GIS system with the "modelica" simulation environment. The analyses demonstrate that the share of heat from CHP generation in the total heat supply can be increased, despite the reduced heating demand, if the configuration and operation of the CHP plant is adapted to the changed load profile.

Lowering the inlet and outlet temperatures for the district heating reduces heat losses in the piping. Although more pumping is needed, a more efficient heat supply can be achieved. The investigations show that the heat losses via the piping can be reduced by up to 15 % if the maximum inlet temperature for the district heating is reduced by 20 K.
The district heating operation can be optimised further by increasing the thermal storage capacity. Distributed storage management, which takes the storage capacity of the district heating network into account, can increase the flexibility in de-coupling electricity and heat generation, so that the CHP operation can be adapted better to the electricity demand without reducing the heat utilisation. This capability is a key to stable operation of future electricity grids with a continually growing proportion of fluctuating energy from renewable sources.

The project has been commissioned by the Freiburger Stadtbau (FSB) housing association and the badenova WÄRMEPLUS utility. It is supported by the German Federal Ministry of Economics and Technology (BMWi) within the "EnEff:Stadt" Programme.

BUILDING-INTEGRATED PV: CALCULATION PROCEDURES, CONCEPTS AND PRODUCTS

Local usage of renewable energy resources plays an important role in reducing CO_2 emission from the existing building stock. In this context, building-integrated photovoltaics (BIPV) plays a key role, particularly with respect to zero-energy buildings, which feature a neutral primary energy balance averaged over the year. Fraunhofer ISE supports the industry in expanding this market segment by developing innovative products and concepts, and new design and optimisation procedures.

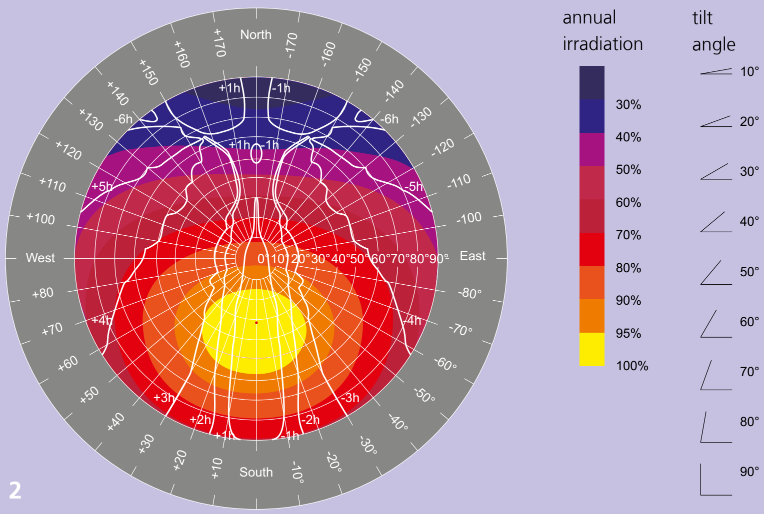
Christof Erban, Karoline Fath, **Tilmann Kuhn**, Andreas Hinsch, Wendelin Sprenger, Helen Rose Wilson, Hans-Martin Henning

1 *The transparent PV module (PV-Shade®) contains PV strips in two planes, which allows it to provide angle-selective solar control, glare protection and visual contact in addition to generating electricity. To determine the annual electricity yield, the irradiation must be determined not only in the front PV plane but also in the second plane behind it.*

The EU and the German Federal Government have set themselves the goal of achieving an almost CO_2-neutral building stock by 2050. The primary energy balance of new buildings should already be nearly balanced from 2020. A marked increase in energy efficiency is required, particularly within the existing building stock. Even after renovation, renovated buildings usually still have a significant primary energy demand, which must be balanced in future by primary energy credits. This can be achieved by appreciable local electricity generation based on photovoltaics, such that not only the roof but increasingly also building façades are used for gaining energy. As a result, the significance of building-integrated photovoltaics (BIPV) will increase markedly in future. At the same time, architecturally satisfying solutions must be developed to ensure long-term and widespread acceptance. Fraunhofer ISE is supporting this trend with new design and optimisation procedures, concepts and the development of innovative products.

Concepts

The integration of electricity from fluctuating renewable energy sources such as the sun and the wind into the European electricity grid is the subject of many research and development activities such as e-mobility, smart grids and storage of electricity in general. However, the compatibility of photovoltaic electricity with the grid can also be increased already at the building level, if measures are taken to prevent all of the PV systems from supplying maximum power at the same time (Fig. 2). An intelligent combination of differently orientated systems can spread out the feed-in period and simultaneously save costs for inverters.



New design and optimisation procedures

- The yield from novel, innovative products with angle-dependent properties that have been optimised for façade applications cannot be predicted with existing calculation methods and programs. Thus, a new calculation method has been developed at Fraunhofer ISE.
- Cost is an important criterion for decision-makers, also in connection with BIPV systems. Within the cluster of excellence, "Solarvalley Mitteldeutschland", we have developed a method to determine the total cost of ownership (TCO) which also takes savings into account which are achieved by replacing building envelope components by photovoltaic modules.
- The total solar energy transmittance (g value) of transparent PV modules is influenced by the energy which is extracted from the façade as electricity and thus does not contribute to warming of the room behind the façade. At present, a procedure is being developed at Fraunhofer ISE which is intended for inclusion in revised standards and takes account of this effect.
- An essential feature of transparent PV modules is visual contact. At present, there are no generally recognised criteria to characterise this property. Extensive user studies have been conducted as the basis for developing an assessment method which quantifies the quality of the outdoor view and can be used for optimisation of transparent PV modules.

2 *Annual yield and time shift of the daily maximum feed-in power from PV systems at a latitude of 48° north (Freiburg). The figure illustrates that e.g. the time of maximum feed-in power can be shifted by 3 h by changing the orientation of the PV system, if a total yield reduction of around 15 % is taken into account.*

Innovative products

- The transparency of currently available transparent PV modules for façades is not optimised with respect to viewing direction. In particular, visual contact to the glaringly bright sun and to the foreground below the horizon is identical. The new PV-Shade® module (Fig. 1) is transparent only for horizontal and downward viewing directions, such that it provides glare protection and solar control. The element is designed particularly for application in the balustrade region of a façade.

In 2011, we succeeded in integrating semi-transparent dye solar cells into façade elements and increasing the cell lifetime (see page 101). This development step represents an important milestone for this potentially very inexpensive PV technology.

LowEx SYSTEMS: INDOOR COMFORT AND ENERGY-EFFICIENT COOLING

Buildings which are cooled and heated via the floor, ceiling or walls in combination with environmental heat sources and sinks have become established in the past few years. Numerous successful and well-functioning examples demonstrate that these systems can provide very comfortable thermal conditions together with high energy efficiency in the usage of renewable environmental energy. However, operating experience and systematic scientific analysis of many projects show that there are still opportunities to optimise the planning, implementation and operation, so that the efficiency potential of these systems can be further exploited.

Martin Fischer, Sebastian Herkel, **Doreen Kalz**, Simon Winiger, Dominik Wystrcil, Sebastian Zehnle, Hans-Martin Henning

Together with industrial and research partners, we measure and analyse the performance of non-residential buildings with reversible heat pumps, which use the ground as a heat source or sink. Long-term measurements and coupled building and system simulations are applied to identify and evaluate strengths and weaknesses in the planning, implementation and operation of these complex technological systems for building services. These factors derived from experience are used in quality assurance procedures.

A cross-sectional analysis of more than ten non-residential buildings shows that thermally activated building systems in combination with the ground as an environmental heat sink provide sufficient cooling energy to guarantee satisfactory thermal comfort and thus high-quality working conditions – provided that constructional and technical measures are already developed jointly during the planning phase and are taken into account during building operation.

1 *"inHaus2" in Duisburg, a research platform of the Fraunhofer-Gesellschaft. The building and the technical building services have been intensively measured and optimised in operation since 2009.*

2 *Cooling plant in "inHaus2". The building is cooled in summer with a reversible heat pump system in combination with an array of borehole heat exchangers and thermally activated building surfaces.*

Cooling energy is mainly provided by direct operation of the borehole heat exchangers (BHEX), with additional active cooling support from ground-connected, reversible heat pumps during periods with a higher cooling demand. As a result, these systems feature a low energy demand for cooling and thus achieve high energy efficiency. Annual coefficients of performance were determined from measurements in the projects to be 4.8 to 5.8 $\text{kWh}_{therm}/\text{kWh}_{el}$ for active cooling (chiller plus primary pump), 10 to 16 $\text{kWh}_{therm}/\text{kWh}_{el}$ for direct cooling (BHEX) and 1.5 to 8.0 $\text{kWh}_{therm}/\text{kWh}_{el}$ for the complete system including the distribution and transfer of cooling energy.

Nevertheless, it is clear that the efficiency of the systems must be further improved, e.g. by consistently optimising the hydraulic systems and system components and by optimised operation of the heat pumps. Our analysis shows that the efficiency of the investigated installations could be increased by about 34 to 50 % by integrated system tuning, efficient operation management of all cooling system components and optimisation with regard to the auxiliary energy. In the "direct cooling" operation mode, this would result in annual coefficients of performance greater than 20.

The "LowEx:Monitor" project is supported by the German Federal Ministry of Economics and Technology (BMWi).

http://lowexmonitor.ise.fraunhofer.de/
www.inhaus.fraunhofer.de

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MONITORING OF ENERGY SUPPLY SYSTEMS INCLUDING HEAT PUMPS

The rising number of novel energy supply systems, which is often accompanied by greater system complexity, demands comprehensive evaluation to provide both the legislator and the user with reliable information on their ecological and economic performance. Heat pump systems in various configurations, e.g. in connection with solar-thermal collectors, are typical for such supply technology. In addition to the overall assessment by annual coefficients of performance, the manufacturers are primarily interested in analyses of operating performance and the identification of optimisation potential. Fraunhofer ISE is conducting numerous monitoring projects to generate such information. Well-founded, representative results are obtained by the broadly based field investigation of more than 200 heat pump systems. Particularly innovative overall concepts, such as the floating plus-energy building in Kalkar, require individual investigation with more intensive measurement.

Danny Günther, Thomas Kramer, **Robert Langner**, Christian Lumm, **Marek Miara**, Jeanette Wapler, Hans-Martin Henning

Monitoring of heat pump systems

Comprehensive analysis of electric heat pumps is carried out by Fraunhofer ISE within the "WP Monitor" project (2009–2013), which is now the third monitoring project in this field. Its predecessors were the "WP Effizienz" project (2005–2010) for monitoring of heat pumps in new buildings, and the "WP im Gebäudebestand" project (2006–2009) for evaluation of heat pumps in existing buildings. Summarising the results, these projects proved that heat pumps often achieve an efficiency which justifies their application as a substitute for fossil-fuelled boilers on the basis of the primary energy demand. However, it was also demonstrated that not all systems reached this goal. The scatter among the results indicates a large potential for optimisation. The most recent monitoring results with higher efficiency values already confirm a learning effect, particularly concerning design and installation. Interested persons can observe real-time operation with the aid of on-line visualisation (Fig. 2).

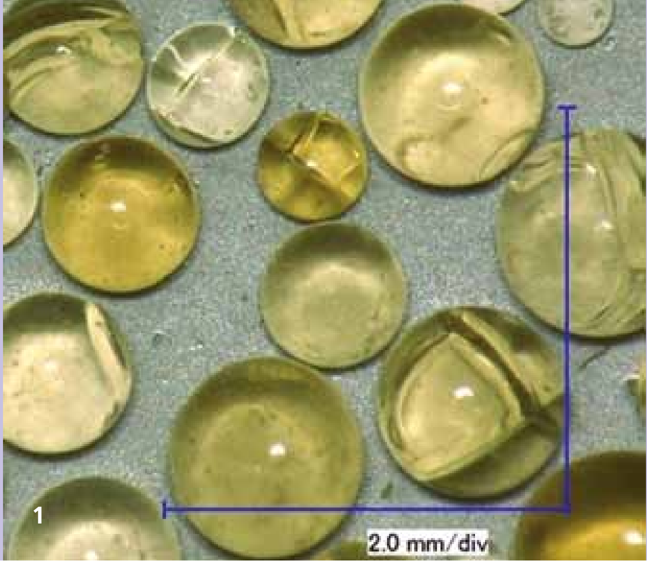
1 *Floating plus-energy building in Kalkar.*

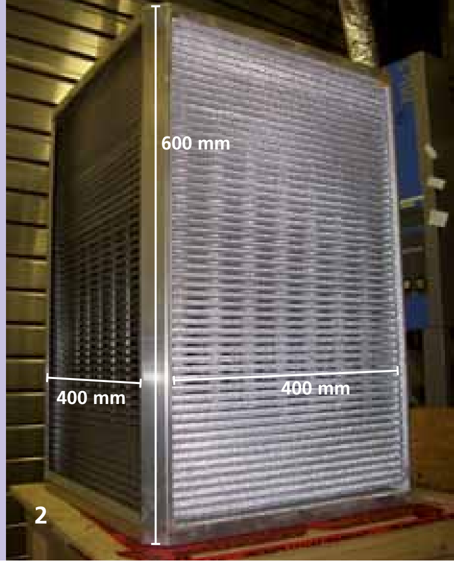
2 *Online visualisation of instantaneous measurement results for heat pump systems.*

Monitoring of a floating plus-energy building

Hülsmann & Thieme, an architectural office in Kleve, has developed a concept for a floating plus-energy building (Fig. 1). The energy concept was prepared together with Fraunhofer ISE, which will also monitor the building for two years. This will determine whether the plus-energy goal was reached. At the same time, the building is serving as a research platform for regenerative energy systems and innovative heating technology. This includes a PV system, a solar-thermal system and a heat pump which uses the lake as a heat source. A total of 105 sensors has been installed, and with measurement data being recorded every 90 s, dynamic processes can also be well observed. Apart from the long-term investigation, this also allows the operating performance to be monitored and optimisation potential to be identified.

www.wp-monitor.ise.fraunhofer.de





HIGHLY EFFICIENT, THERMALLY DRIVEN AIR DEHUMIDIFICATION

Building air-conditioning guarantees control of temperature and humidity conditions in rooms. Air dehumidification can be responsible for a significant share of the energy demand for electrically driven, standard air-conditioning technology. The application of thermally driven sorption processes presents a resource-conserving alternative. The successfully developed ECOS process (Evaporatively Cooled Sorptive Heat Exchanger) combines dehumidification of the input air by a sorbent with temperature reduction by evaporative cooling. The very effective cooling and dehumidification, combined with efficient application of the driving thermal energy, was demonstrated experimentally with prototypes.

1 *Silica gel attached to the heat exchanger for sorptive air dehumidification.*

2 *Prototype of a cross-current heat exchanger with a sorptive coating on the inlet air side.*

Constanze Bongs, Alexander Morgenstern, Hans-Martin Henning

The work at Fraunhofer ISE aimed to successfully demonstrate the patented process, concentrating on developing the key component for the process, the sorbent-coated heat exchanger. The inlet air side of a cross-current heat exchanger was coated with silica gel as the sorbent. If humid outdoor air flows through the sorbent-coated inlet air channels, water vapour from the air is adsorbed onto the pore walls of the sorbent, releasing heat. At the same time, water is sprayed into the outlet air channels of the heat exchanger. Evaporation of the water causes the temperature of the outlet air to fall. In this way, heat can be transferred from the warm inlet air to the cold outlet air, so that the inlet air can be simultaneously cooled and dehumidified to create comfortable conditions. As the sorbent becomes increasingly moist, it must be dried by solar heat (desorption) to keep the process functioning. In order to provide conditioned air continuously, two sorption heat exchangers are operated alternately in a single unit.

Different prototypes of sorption heat exchangers were characterised in a test rig for air-conditioning equipment, which was constructed for this purpose at the "Solarhaus" in Freiburg. The intended application is air-conditioning of free-standing houses or smaller offices with air flow rates of about 400 m³/h. Under standard design conditions for Germany (outdoor air conditions: 32 °C / 12 g/kg – temperature/humidity), cooling to 24.5 °C with dehumidification to 7.5 g/kg was achieved, corresponding to a cooling power of 2.33 kW and a thermal coefficient of performance (COP_{th}) of 0.97. The value of this process for hot and humid climatic zones (outdoor air conditions: 39.3 °C / 17 g/kg) was also demonstrated with cooling by up to 14.2 K and dehumidification by up to 10.2 g/kg. Based on these results, a technological demonstration unit was developed, which is being tested within a co-operation project at SERIS (Solar Energy Research Institute of Singapore).

The "Neues, hocheffizientes Verfahren zur sorptiven Luftentfeuchtung (ECOS)" project is supported by the German Federal Ministry of Economics and Technology (BMWi).

COOLING STORAGE UNIT WITH PHASE-CHANGE SLURRIES

A large phase-change slurry storage unit was taken into operation for the first time in Germany at Imtech Deutschland GmbH & Co. KG in Hamburg. Micro-encapsulated paraffin, which is produced by BASF, serves as the phase-change material. The melting temperature of the paraffin is between 22 and 28 °C. The heat storage capacity of the slurry is about 16 kWh/m³, such that about twice as much heat can be stored as in a water tank of the same volume, for a comparable temperature difference. In addition to pre-heating or pre-cooling inlet air, the slurry can also be used in technical applications, e.g. to cool machines.

Stefan Gschwander, Thomas Haussmann, Peter Schossig, Laura Vorbeck, Hans-Martin Henning

Phase-change materials (PCM) can store and release heat at an almost constant temperature, whereby use is made of the phase transition between liquid and solid states. Various materials are used as PCM. Paraffins are hydrophobic PCM, which are well suited for use in a phase-change slurry (PCS). These paraffins are micro-encapsulated by BASF and can then be mixed with a carrier liquid such as water to form a suspension, independent of the physical state of the paraffin. The suspension can be pumped through hydraulic components like pipes and heat exchangers in the same way as a conventional cooling fluid.

In a project devoted to the development of cooling storage units on the basis of PCS and micro-encapsulated PCM, Imtech Deutschland GmbH & Co. KG constructed a cooling system with the support of Fraunhofer ISE, which includes a 5 m³ tank that is filled with a PCS which is cooled by a compression chiller. The PCS, with 30 % encapsulant content by weight, was characterised by Fraunhofer ISE and tested for stability. It achieved a heat capacity of 60 kJ/kg with a melting range from 22 to 28 °C. The viscosity changed from 30 to 80 mPa s on transition from the liquid to the solid phase and the density increased from 940 to 980 kg/m³. Stability over 100 000 cycles was demonstrated in the laboratory. The installed equipment will be measured in detail in order to gain information about real operating performance and to identify potential for optimisation.

In particular, cooling applications which must operate with a small temperature difference could be equipped with more compact tanks and operate more efficiently by using this technology.

1 *Phase-change slurry storage system with the 5 m³ tank (left) and the heat exchanger (right), installed at Imtech Deutschland GmbH & Co. KG in Hamburg.*

2 *Phase-change slurries consist of a phase-change material and a carrier liquid. A dispersion is formed which remains fluid, independent of the physical state of the phase-change material. Its viscosity depends on the concentration of dispersed PCM.*

The project is supported by the German Federal Ministry of Economics and Technology (BMWi).

1

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ADSORPTION OF ALCOHOLS ON ACTIVATED CARBON FOR HEAT PUMPS

In addition to the adsorption of water, the use of alternative refrigerants such as methanol or ethanol offers interesting opportunities to drive heat pumps. The main advantage is the possibility to use source temperatures below 0 °C. Activated carbon can be used as the adsorbing medium, which we prepare in our laboratories from e.g. walnut shells or grape pips.

1 *Activated carbon produced from biomass.*

2 *Raw materials for production of activated carbon.*

Max Baumgartner, **Stefan Henninger**, Gunther Munz, Peter Schossig, Hans-Martin Henning

Water is generally used as the working fluid in commercially available adsorption chillers and heat pumps. The advantages of water are its very high heat of evaporation and its non-toxicity. Nevertheless, its high freezing temperature compared to that of organic refrigerants and the low vapour pressure at low temperatures present disadvantages. They restrict its use in chillers, but also in heat pumps, to applications with temperatures above 0 °C on the low-temperature side. However, the temperature range below 0 °C is very interesting, particularly for heat pump applications, as the equipment complexity and thus investment costs can be significantly reduced if air is used as the low-temperature heat source. For this reason, methanol and ethanol are also being investigated at Fraunhofer ISE for use as working fluids in adsorption systems.

Adsorbents of activated carbon, which can also be produced in principle from cost-effective raw and waste biomass materials by simple and well-known processing technology, revealed great potential. Using materials which we synthesised in our laboratory, we achieved very high adsorption of the working fluid of up to 0.249 g per gram of adsorbent (operating conditions: 120 °C driving temperature, 29 °C average temperature and -5 °C evaporator temperature), compared to the values for conventional working pairs such as water/silica gel and water/zeolite. The higher vapour pressure of the alcoholic refrigerants compared to water also increases the adsorption rate, as the mass transport processes such as flow and diffusion proceed significantly faster under higher pressure gradients. As the performance of an adsorption chiller is proportional in a first approximation to the working fluid uptake, the heat of evaporation and the adsorption rate, it can be anticipated that compact equipment with a high power density can be achieved with this material combination. For technical implementation, it is essential that the materials be very stable. Initial investigations on possible decomposition reactions and the long-term stability of the organic refrigerant have delivered encouraging results; this work is still continuing for promising material combinations.

The project is supported by the German Federal Ministry of Economics and Technology (BMWi).

NOVEL SORPTION MATERIALS AND COATINGS

Thermally driven chillers and heat pumps present an attractive approach for energy-efficient and cost-effective cooling and heating of rooms. Parallel to the development of novel sorption materials, e.g. metal-organic frameworks (MOF), for these applications, the deposition of these functional materials to the surfaces of heat exchangers represents another important field of work. At Fraunhofer ISE, not only have very promising novel materials been developed but also coating processes to deposit these materials onto heat exchanger structures.

Stefan Henninger, Felix Jeremias, Harry Kummer,
Peter Schossig, Hans-Martin Henning

In recent years, we have intensified our efforts to evaluate and synthesise new materials, aiming for the highest possible adsorption capacity. The use of metal-organic frameworks (MOF) is the most recent development. Compared to previously investigated materials, significantly higher adsorption loads were achieved. One combination was identified which features a maximum loading of 1.43 kg/kg, meaning that the material can adsorb more than 1.4 times its own mass of water. Simultaneously, some composites show a so-called "breathing effect", i.e. the internal volume of the materials increases similarly to human lungs, such that they can adsorb significantly more water above a certain pressure point.

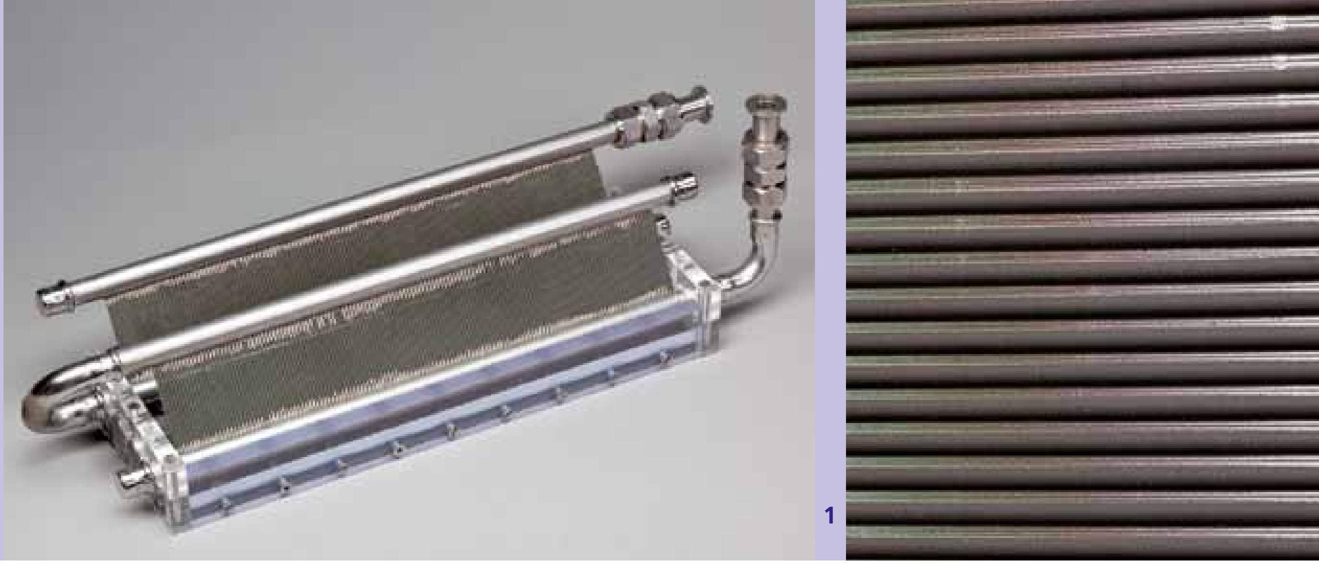
In addition to water adsorption properties, heat and mass transport is decisive for the power density which can be achieved by the systems. We have thus worked intensively on coating processes for support structures to achieve good thermal coupling to the heat exchanger while ensuring that the adsorption centres remain easily accessible. We succeeded in depositing different sorbents such as zeolites or zeolite-type materials, but also novel metal-organic frameworks, onto different support structures and with varying ratios of binder to sorbent, and achieving good stability and durability. Stringent specifications must be met, particularly concerning the thermal and thus the mechanical stability of the coating. For example, the coating must survive several thousand cycles between high (140 °C) and low (30 °C) temperatures without damage. The first application tests of these composite materials on a laboratory scale were very promising.

The project is supported by the German Federal Ministry of Economics and Technology (BMWi).

1 *Coatings of support structures containing different sorbent materials.*

2 *Novel sorption material based on metal-organic frameworks.*

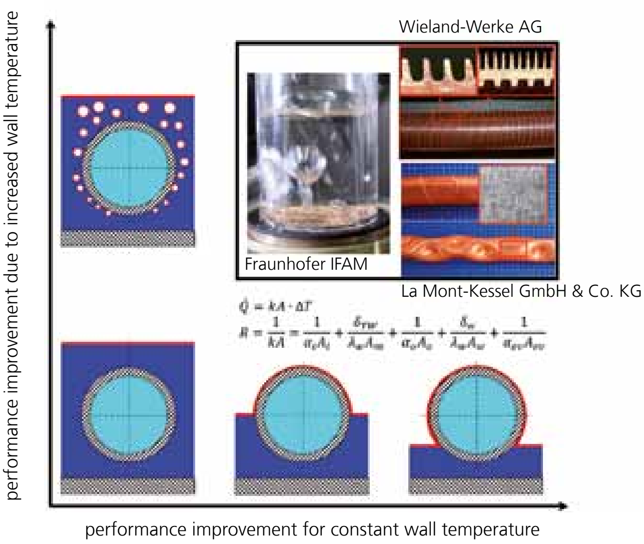
3 *Coatings with varying ratios of binder to sorbent, produced at Fraunhofer ISE. This demonstrates the great flexibility of the system that we have developed with a stable coating, even with a binder proportion of only 2 wt-% (binder proportion from left to right: 25 %, 10 %, 5 %, 2 %).*



EVAPORATOR DEVELOPMENT FOR ADSORPTION CHILLERS

The development of thermally driven adsorption chillers has been a research focus at Fraunhofer ISE for many years. The goal is to achieve higher power density combined with high energy efficiency and long-term stability. On the one hand, this demands materials that are specifically designed for the application in question; on the other hand, efficient heat exchanger structures must also be implemented. A key component, which offers great potential for increasing the overall power density, is the evaporator, which was investigated for water as the cooling agent in the "SORCOOL" project.

Lena Schnabel, Peter Schossig, **Kai Thomas Witte**, Hans-Martin Henning

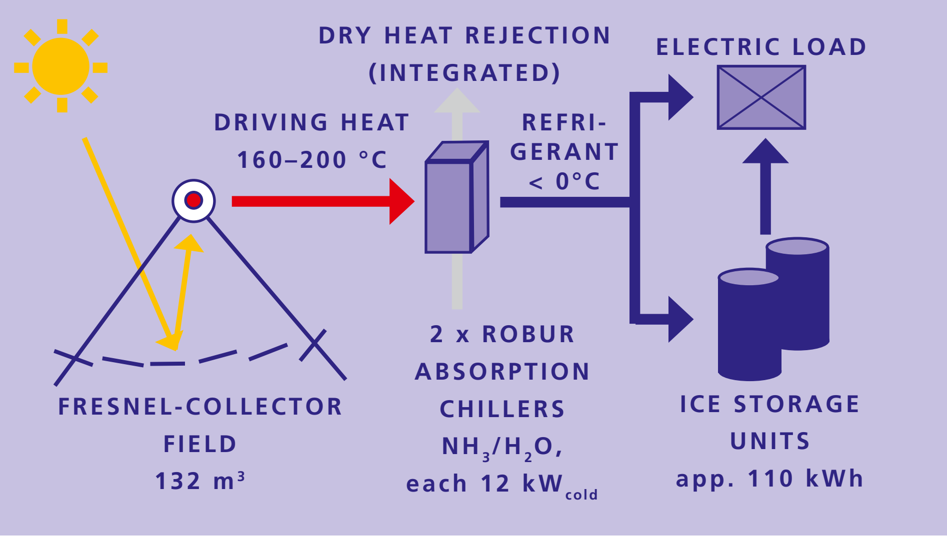


2 *Approaches to improve the outer heat transfer of an immersed evaporation pipe. Detail: nucleate boiling on a 3D structure of short metal fibres, which was produced at Fraunhofer IFAM (left) and a high-performance evaporation pipe (right).*

1 *Installation with two capillary mesh evaporator structures in the test rig. Fluid flows across the entire surface of the structures, which are produced by the Spörl company. Evaporation occurs from the mesh structure, which draws the refrigerant out of the pool by capillary forces.*

If water is used as refrigerant, evaporation occurs at low temperatures and pressures (less than 25 mbar). Classic constructions such as fin heat exchangers or piping bundles are generally used for the heat exchangers and evaporation takes place into an open volume to minimise pressure-induced losses. Detailed investigations were made at Fraunhofer ISE to determine which heat transfer rates can be implemented for different boiling regimes (convective, bubbling) and small temperature differences. In the project "SORCOOL", capillary-assisted evaporation was identified as a suitable operating mode requiring only very simple equipment, which can already be implemented well with commercially available structures. By using pipes with zones of microscopic and macroscopic structures (Fig. 1), the evaporation performance was increased by up to fourteen times compared to smooth reference pipes. The formation of thin water films by spraying or capillary distribution structures is decisive. Nucleate boiling can also be achieved with suitable structures. To increase the overall efficiency, not only must the heat transfer on the evaporation side be improved but also the heat transfer to the transport fluid and the reduction of pressure-induced losses must be taken into account. At present, capillary tube structures that are integrated into a metallic mesh (Fig. 1) are being investigated as an approach to solve these problems. This type of concept promises significantly reduced component volumes accompanied by smaller driving temperature differences and pressure losses.

The work was supported by the German Federal Ministry of Economics and Technology (BMWi).



SOLAR COOLING WITH CONCENTRATING COLLECTORS

Solar-thermally driven cooling systems can still benefit from further development, particularly for the low and medium power range. Further improvement of the multi-facetted systems in this power range and identification of commercially applicable solutions were the objectives of the EU-funded "SOLERA" project. The core of this four-year project comprised the planning, construction, operation and evaluation of three test systems in Germany, France and Italy. The combination of a concentrating Fresnel collector with thermally driven chillers was tested in Freiburg. New application areas, e.g. for industrial processes or food cooling, can be accessed with this technology.

Alexander Morgenstern, **Christine Weber**, Edo Wiemken, Hans-Martin Henning

Twelve partners from research institutions and the industry participated in the "SOLERA" project under the leadership of Fraunhofer ISE. In addition to activities to support planning and market introduction of solar cooling, the project encompassed the construction and technical monitoring of three systems applying different types of collector and cooling technology.

One of the systems was installed near Freiburg. The special feature of this system is the combination of a linearly concentrating Fresnel collector (aperture area of 132 m²) with two thermally driven chillers which use ammonia as the refrigerant and water as the sorbent (nominal cooling power: 12 kW each). Temperatures of up to 400 °C can be reached with these single-axis tracking collectors, so they are very well suited for application in industrial processes. In the demonstration project, the chillers, which are operated with driving temperatures of 160–200 °C, cool the refrigerant to temperatures below 0 °C and either charge four ice storage

1 Linearly concentrating Fresnel collector manufactured by Industrial Solar GmbH, Germany. The collector provides heat at temperatures of up to 400 °C for process heat applications.

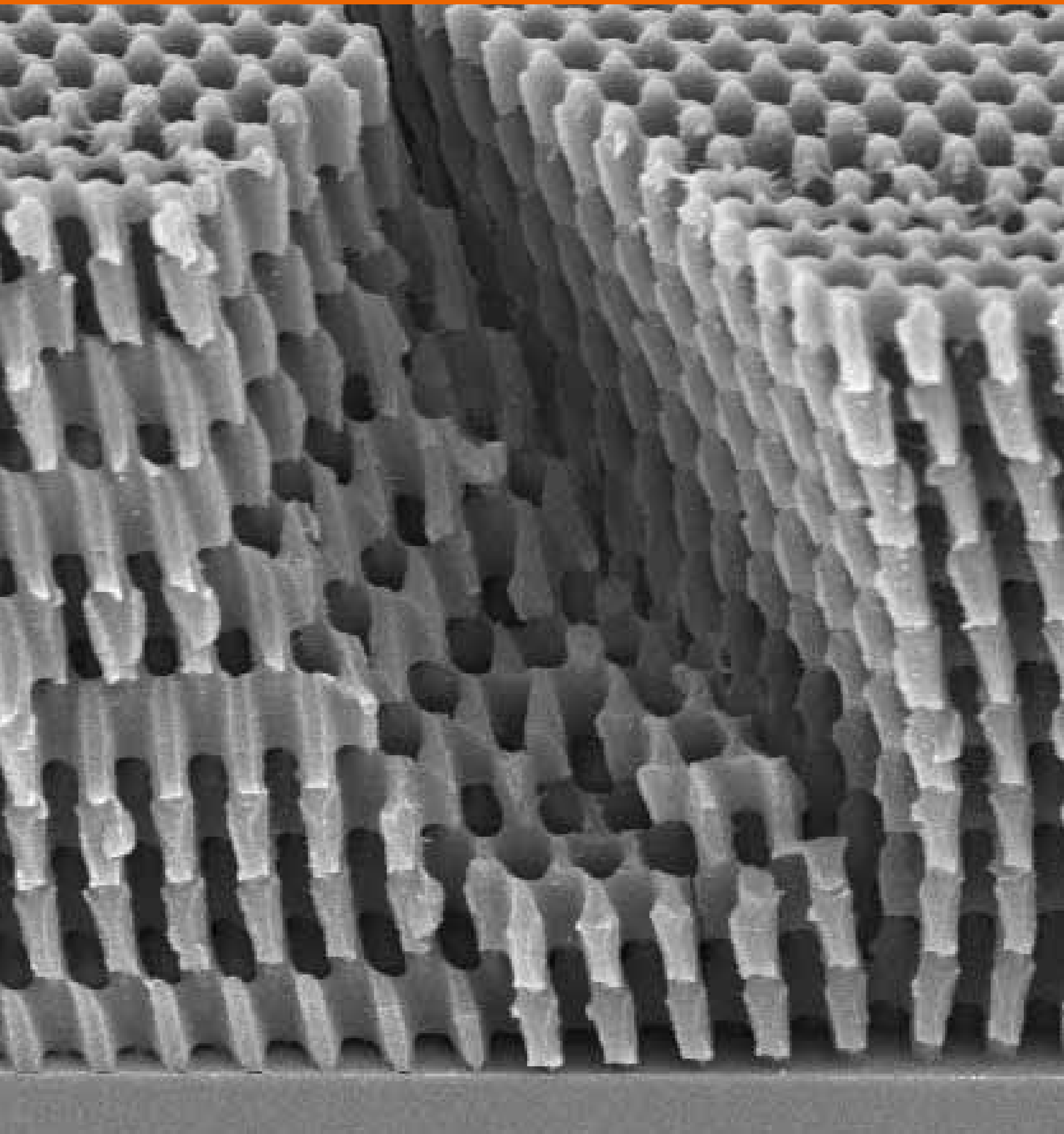
2 The Fresnel collector serves as the heat source to drive the two absorption chillers. With driving temperatures up to 200 °C, the refrigerant can be cooled down to -12 °C. It can be fed directly to the cooling load and/or used to charge the ice storage unit, which can provide cooling power when there is less solar radiation. (Manufacturer of the chillers with ammonia/water as the working couple: Robur, Italy)

units (each with a volume of 300 l; total storage capacity of app. 110 kWh) and/or cool the installed load directly. This approach allows cooling power to be provided even when there is no solar radiation available, increasing the number of operating hours and the efficiency of the installed system. The hydraulic concept allows the two chillers to be operated in series or in parallel, depending on the cooling demand and the solar radiation supply.

Operation of the test system demonstrated that the system components used were technically mature and operated reliably. On a sunny day of operation in August, the collector achieved e.g. a peak power exceeding 60 kW, of which around 42 kW was used as the driving power for the chillers, and the cooling power amounted to 24 kW. As coolant temperatures below 0 °C are reached, an application for foodstuff cooling in southern regions is particularly interesting. However, it will still be a challenge to combine the system components into a complete system in the planning and operation phases. Further work leading toward standardisation will be needed to enable successful application of this technology on a broad basis in sunny regions.

The project was supported by the European Commission.

BETTER WITH GOOD OPTICS



APPLIED OPTICS AND FUNCTIONAL SURFACES

Solar energy systems convert solar energy, which is incident on the earth as electromagnetic radiation, into thermal, electric or chemical energy. We develop optical components and systems to better transmit, reflect, absorb, filter, redirect or concentrate solar radiation, depending on the requirements.

The broad bandwidth of the solar spectrum, covering wavelengths from 0.3 to 2.5 µm, and the need to produce optical components and systems inexpensively over large areas, present major and diverse challenges. To overcome these, we follow novel approaches which combine materials research, optical design and production technology. In addition to optical know-how, knowledge of material properties and close co-operation with our clients, comprehensive and specific knowledge of the corresponding solar energy systems is necessary to transfer the approaches successfully to new products for solar technology. Fraunhofer ISE provides excellent opportunities for the synergetic interaction needed for this.

The interdisciplinary topic "Applied Optics and Functional Surfaces" is the basis for several market sectors of solar technology: windows and façades, solar thermal collectors, concentrator systems for photovoltaics and solar-thermal collectors. Our expertise is also appreciated by clients who do not come from the solar sector. For example, we provide support for lighting and display technology.

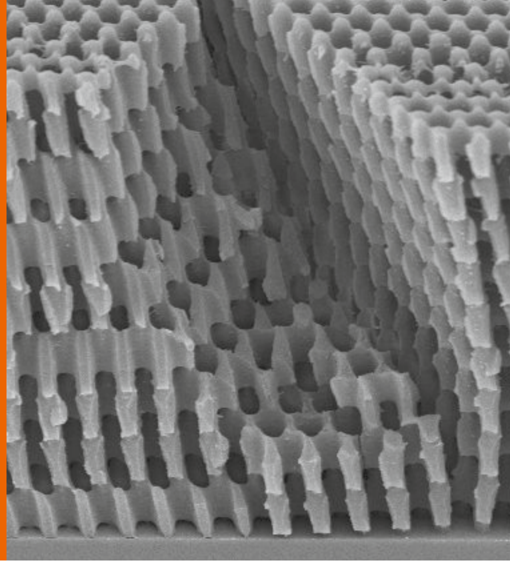
Effective control of the light and solar energy fluxes through the façade is very important for energy-efficient buildings with large glazed areas. Switchable coatings on window panes allow the window transmittance to be changed over a wide range. As non-mechanical solar-shading systems, they offer advantages with regard to viewing quality and vulnerability to wind damage, for example. Coatings to reduce reflection or soiling increase the transmittance.

Glazing units with very good thermally insulating properties can be achieved with highly transparent low-emissivity coatings and inert gas fillings, but also with vacuum or transparent insulating materials. If the thermal insulation is very good, they show condensation and even frost on the external surface during certain days in winter. In order to reduce these unwanted side-effects, stable low-e coatings are being developed for the outdoor surface. Other transparent, electrically conductive coatings are required as electric contacts for thin-film photovoltaics and organic solar cells.

Microstructured surfaces form the basis for solar-control systems which reflect undesired direct solar radiation but still transmit diffuse daylight. Photonic gratings and light-trapping structures increase the efficiency of organic and silicon solar cells. In photovoltaic concentrator modules, solar radiation is concentrated onto tiny high-performance solar cells. We optimise concentrator optics with regard to its efficiency and cost.

The combination of micro-optical know-how and interference lithography over large areas has made a sector outside of solar technology interesting to Fraunhofer ISE, namely display technology. Here, we are working on micro-structured polymer films which improve the brightness and contrast of displays. Light redirection and light scattering based on both imaging and non-imaging optics are central topics in lighting technology. Drawing on our work for daylighting technology, we also offer our expertise in optical materials and surface properties for optical design in artificial lighting technology.

Over the past years, we have continually extended our modelling capacity. It encompasses fundamental physical models such as effective-medium theory, rigorous and scalar diffraction theory, scattering theory, thin-film methods,



geometric and non-imaging optics, as well as planning tools, e.g. for lamp design. This means that we can respond quickly and efficiently to clients' enquiries by determining the feasibility of a desired optical component. Vacuum coating and micro-structuring processes are available to us as production methods. Our characterisation methods not only include standard procedures but also use special equipment, e.g. to determine the accuracy of reflector forms with scanning fringe reflectometry or quantify the degree of reflector soiling. Whenever needed, we extend the palette of services by close co-operation with recognised research institutions within and outside the Fraunhofer-Gesellschaft.

Special facilities:

- vacuum deposition system for quasi-industrial production of complex coating systems over large areas (140 x 180 cm^2)
- interference-lithography equipment for homogeneous production of microstructures and nanostructures over areas of up to 120 x 120 cm^2
- optical measurement technology: spectrometry, goniometry, light-scattering measurements, refractometry, luminance measurements with imaging methods, fringe reflectometry, special measurement facilities for concentrating optics, quality control for production
- surface characterisation: optical profilometry, scanning electron microscopy, atomic force microscopy, Auger electron spectroscopy

Scanning electron micrograph of a three-dimensional photonic crystal in photoresist, which was produced by interference lithography with four superimposed electromagnetic waves. The angle-selective and spectrally selective properties of photonic crystals can contribute to more efficient light management in solar cells.

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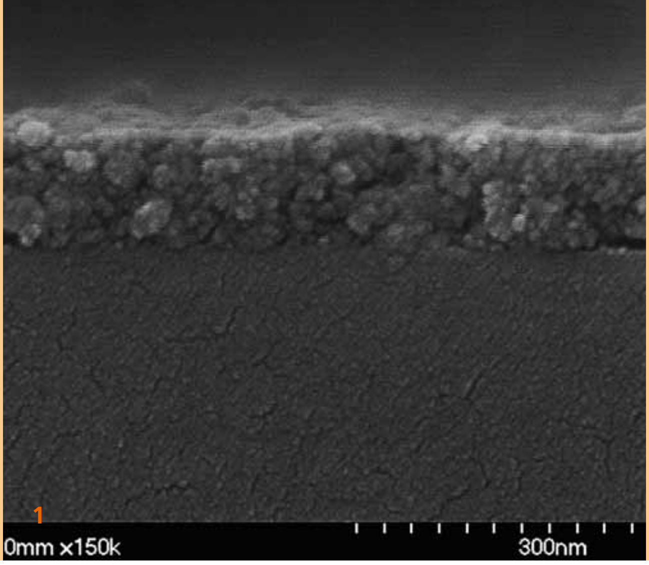
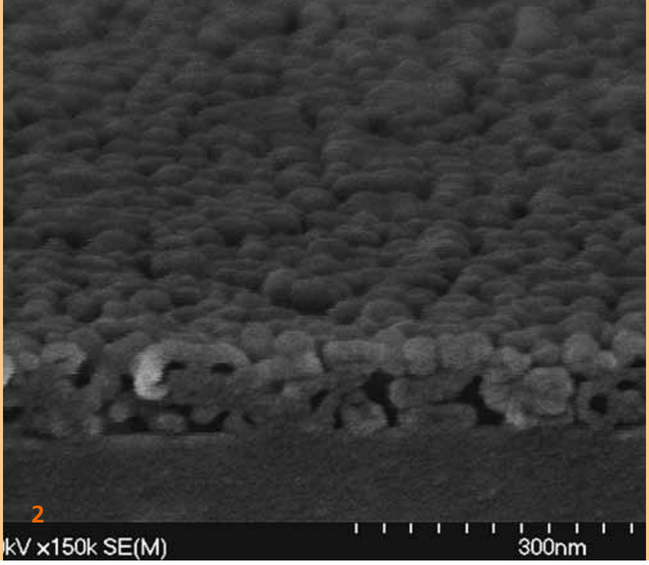
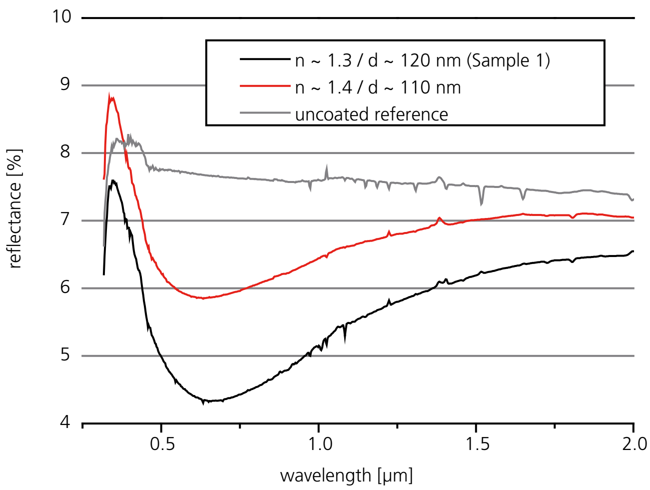




CHARACTERISATION OF NANOPOROUS ANTI-REFLECTIVE COATINGS

1 – 3 *Scanning electron micrographs of nanoporous anti-reflective coatings. All three coatings feature comparable porosity and thus similar effective refractive indices (n ≈ 1.3) and similar reflectance. The pore size increases from sample 1 (Fig. 1) to sample 3 (Fig. 3). The pores of sample 3 are so large that this coating is no longer optically homogeneous for short-wavelength radiation and causes slight light scattering.*



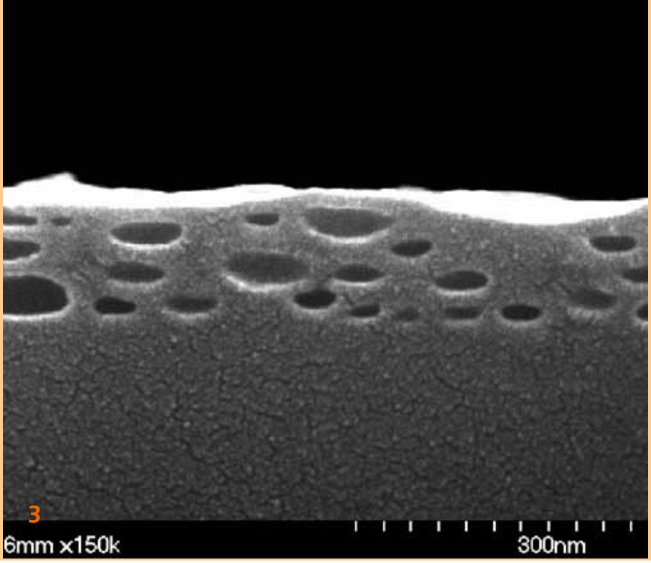
5 *Spectral reflectance of glass panes coated on one side. An anti-reflective coating with high porosity (e.g. sample 1 in Fig. 1, black) shows a significantly better anti-reflective effect than a coating with lower porosity (red). The reflectance of an uncoated reference glass pane (grey) is shown for comparison.*

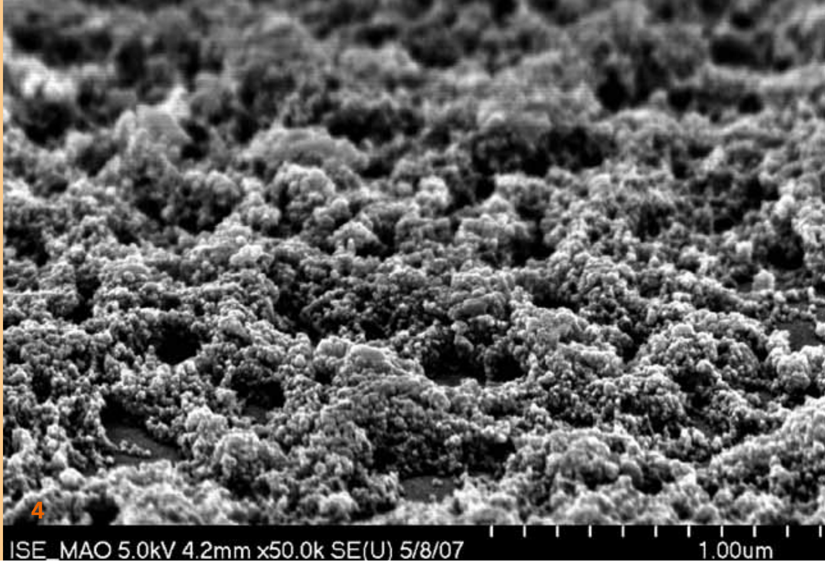
Reducing the reflection from the glass surfaces of PV modules or solar-thermal collectors increases the optical efficiency significantly. At the same time, higher transmittance for architectural glazing enables higher solar gains, saving energy for space heating. Stable materials with a low refractive index are needed to reduce the reflectance of glass surfaces over a wide spectral range. These requirements are met with nanoporous anti-reflective coatings based on SiO_2. We apply highly accurate and comprehensive analytical methods to evaluate the functionality, quality and durability of such coatings

Benedikt Bläsi, Walther Glaubitt*, Volker Kübler, Angelika Schmitt*, **Andreas J. Wolf**, Werner Platzer

* Fraunhofer ISC

The reflectance of glass surfaces can be reduced over a wide spectral range by so-called λ/4 coatings or graded-index coatings (Fig. 5). In both cases, materials with a very low refractive index ($n < 1.35$) are needed. The key to adjusting the refractive index is found with so-called "effective media": These are composite materials, in which the dimensions of the individual structures are significantly smaller than the wavelengths of light. The optical properties of the constituent materials then result in a homogeneous effective refractive index. Indices in the relevant range can be obtained with nanoporous coatings based on SiO_2. The anti-reflective effect



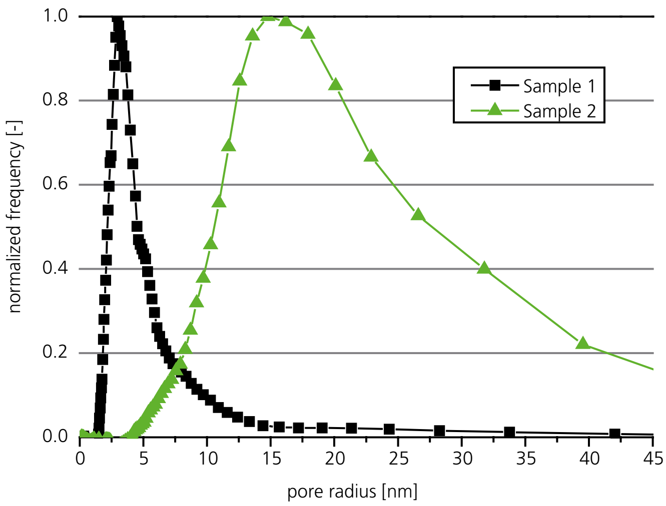


is determined by the refractive index together with the coating thickness. The optimal thickness for λ/4 coatings is in the range between 110 and 150 nm.

The coatings illustrated in Figures 1 to 4 have been developed for outdoor applications and are thus exposed to the weather. The adsorption and desorption of moisture under varying air humidity conditions depend directly on the pore dimensions. The incorporation of moisture changes the effective refractive index and thus the reflectance of the coatings. This effect is exploited for ellipsometric porosimetry. By applying this method, we can determine the distribution of pore geometry (Fig. 6), which has a decisive effect on the stability of the coatings. With the help of optical simulation tools, we can both design coating stacks and model measurement data. This allows us to confirm the consistency of measurement results and the coating properties derived from them by theoretical data.

The work was supported by the German Federal Ministry of Economics and Technology (BMWi), CentrosolarGlas AG and Merck KGaA.

4 *Example of an inhomogeneous anti-reflective coating. The agglomerations of porous material result in a superimposed microstructure which causes scattering.*



6 *Pore radius distribution of sample 1 (black, Fig. 1) and sample 2 (green, Fig. 2), calculated from the adsorption curve determined by ellipsometric porosimetry.*

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HIGH-TEMPERATURE CORROSION OF COATINGS FOR SECONDARY REFLECTORS

Secondary reflectors in solar-thermal power plants focus sunlight which has already been concentrated by primary reflectors. Silver is used as the reflective material due to its high reflectance. The high radiation intensity causes the secondary reflectors to reach high temperatures which induce corrosion according to a mechanism which will be described in the following article. Knowledge of the mechanism allows measures to be derived for its suppression.

Kilian Dallmer-Zerbe, **Andreas Georg**, Wolfgang Graf, Elisabeth Klimm, Marius Kühne, Werner Platzer

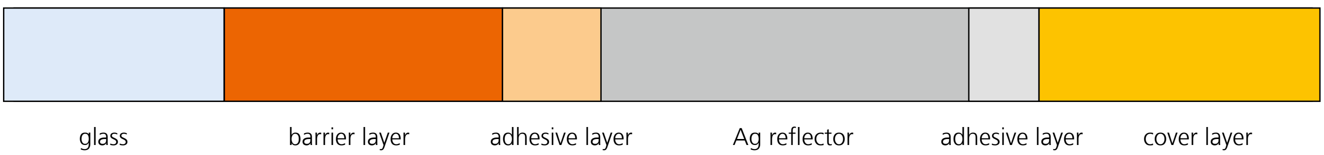
In Fresnel collectors, which are applied in one specific type of solar-thermal power plant, secondary reflectors are used to further focus the sunlight. These reflectors can reach temperatures of up to 300 °C. This poses a challenge for the reflective coatings. To investigate it, a silver layer was deposited together with barrier and adhesion layers by sputtering to form a multi-layer stack on glass at Fraunhofer ISE (Fig. 5).

Although silver is a noble metal, it can still degrade. The best-known form is "tarnishing" due to reaction with H_2S from the atmosphere. This was suppressed by suitable barrier layers on the air side. In addition, a barrier layer toward the substrate is needed to prevent ions from diffusing out of the glass.

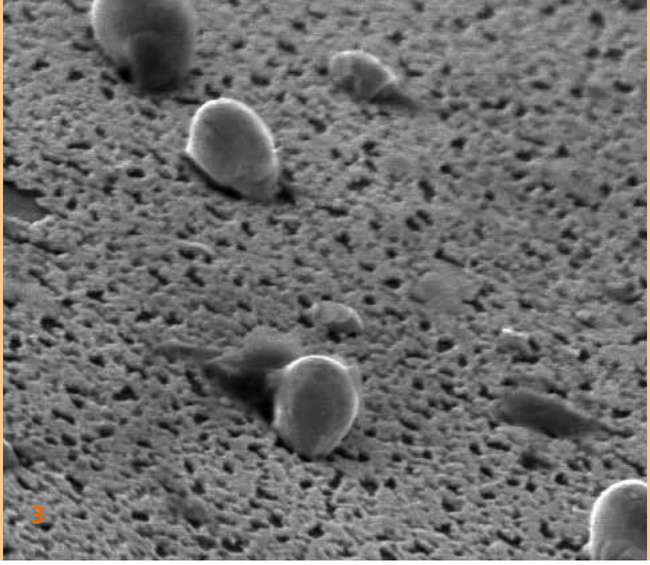
A further degradation mechanism is pinhole corrosion, which can assume varying forms. Two main types are frequently observed: the formation of a few large defects and the formation of many small pinholes (Fig. 1 and 2). An essential effect for the mechanism of this corrosion is the tendency of silver layers to agglomerate. Figure 3 shows a scanning electron micrograph of an agglomerated silver layer without a cover layer after one hour at 450 °C.

This agglomeration process can be suppressed by coating the silver layer with a cover layer. However, this protective function is destroyed at local "hillocks", e.g. dust particles, resulting in large defects. Silver squeezes out from beneath the cover layer, the interface energy between the silver and the cover layer decreases and the defect grows. This process can be retarded by increasing the interface energy between the silver and the cover layer by suitable intermediate layers. The small defects are assumed to be induced by thermal stress, which causes the silver layer to arch and then detach (Fig. 4).

Thermal stress in individual layers was determined by measuring the curvature of thin, coated substrates. By varying the substrate material, it was possible to estimate the elasticity module and the thermal expansion coefficient for the very thin layers (layer thickness of about 100 nm).



5 *Schematic sequence of layers in a reflective coating for a first-surface reflector with high-temperature stability.*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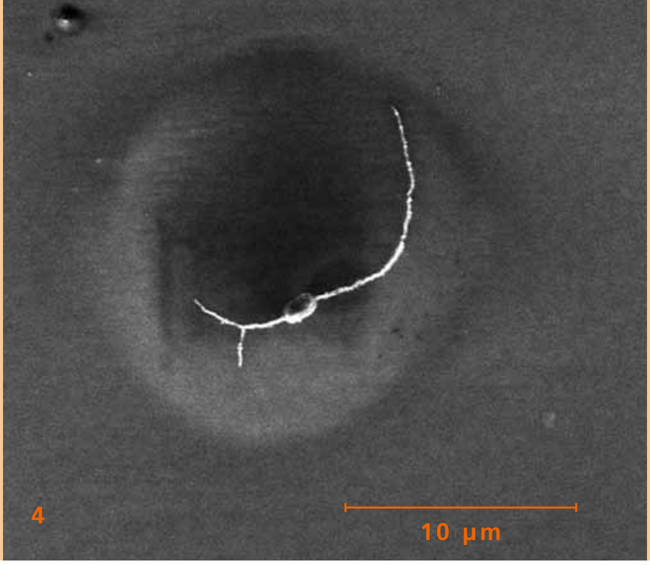
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As expected, low coefficients of expansion were obtained for the dielectric layers that are used as barriers, although the values deviated from those for the bulk material. Silver is characterised here by a large coefficient of expansion, so is critical on glass substrates with low expansion coefficients. Nevertheless, we succeeded in modifying the deposition process and reducing the expansion coefficients to a third of the original value.

Intrinsic stress, such as that caused by the deposition process, can also aggravate the degradation. This was reduced by selecting suitable materials and modifying the processing sequence.

Combination of these approaches resulted in reflective coatings which were stable at a temperature of 250 °C. At a temperature of 350 °C, the solar reflectance decreased by 7 % over five months for a modified layer which showed pinhole corrosion. By contrast, the type with large defects degraded by only 1.5 % after modification.

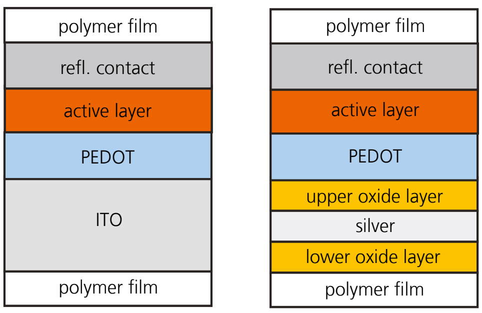
Further approaches to improve the stability are currently being investigated. The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).

1 *Pinhole corrosion of reflector layers with a few large defects after heating at 350 °C for 3800 h.*
2 *Pinhole corrosion of reflector layers with many small pinholes after heating at 350 °C for 3800 h.*
3 *Scanning electron micrograph of a silver layer without cover layers after heating for one hour at 450 °C.*
4 *Scanning electron micrograph of a small pinhole defect.*

TRANSPARENT ELECTRODES WITHOUT ITO FOR ORGANIC SOLAR CELLS

The usage of transparent electrodes based on indium tin oxide (ITO) represents a major cost factor for organic solar cells. In the following article, an alternative electrode based on silver will be presented, which can easily be upscaled and presents not only cost advantages but also better electrical and mechanical properties. The so-called silver electrode consists of a thin silver layer embedded in oxide layers. The multi-layer configuration allows it to be adapted particularly well to the requirements of the individual component. Furthermore, the silver electrode can be manufactured cost-effectively on a large scale on polymer films or on glass.

Andreas Georg, Leonard Kraus, **Thomas Kroyer**, Hans-Frieder Schleiermacher, Uli Würfel, Birger Zimmermann, Werner Platzer



2 Stack configuration of an organic solar cell with an ITO transparent electrode (left) and with the transparent silver electrode as an inexpensive substitute for ITO (right). A silver electrode can be used for extracting electrons as well as holes by suitable choice of the top oxide work function.

1 A transparent silver electrode deposited onto PET. Averaged over the spectral response range of organic solar cells, the silver electrode reaches optical transmittance values of up to 87 % and a sheet resistance below 10 Ω. Due to its nanocrystalline layer structure, the electrode is very elastic and is thus particularly well suited for flexible applications with multiple bending cycles.

A thin silver layer (app. 10 nm thick), which is embedded between two or more oxide layers (Fig. 1 and 2) was used as a transparent electrode without ITO. Whereas the lower oxide layer is primarily responsible for adhesion to the polymer film substrate, the silver guarantees electrical conductivity of the multi-layer stack. The most demanding specifications must be met by the upper oxide layer. It must be at least somewhat electrically conductive and feature the necessary chemical stability when acidic PEDOT:PSS is applied. In addition, the work function must be appropriately adjusted for electronic coupling to the energy bands of the electrons or holes in the active layer, which was achieved by an appropriate choice of the oxides and their stoichiometry. The optical properties of the silver electrode were optimised to obtain maximum absorption in the active layer of each type of solar cell. This can be achieved by selecting oxides with suitable refractive indices and optimising the oxide thickness.

Various silver electrodes were successfully produced for application as transparent cathodes and anodes of organic solar cells. In each case, the efficiency value of the reference cell with ITO was at least equalled. Preliminary results indicate better long-term stability than with ITO.

A lithographic process and laser structuring were successfully tested for structuring the electrode as needed for series connection. The silver electrode can be produced on industrial strip coating equipment and integrated as a semi-finished product into the roll-to-roll cell manufacturing process.

FRESNEL LENSES WITH HIGH EFFICIENCY DESPITE TEMPERATURE VARIATION

In flat photovoltaic modules, sunlight is collected by large-area semiconductors and converted into electricity. Concentrating photovoltaics (CPV) reduces costs by using only tiny solar cells and covering the large area with optical components which focus light onto the cells. The weather at the power plant location affects the temperature of the optics and thus its performance. With the help of computer simulations and accurate measurements, we have succeeded in developing concentrating Fresnel lenses with significantly lower thermally induced losses than conventional Fresnel lenses. They can contribute towards increasing the efficiency of a CPV power plant and reducing the levelised costs of electricity.

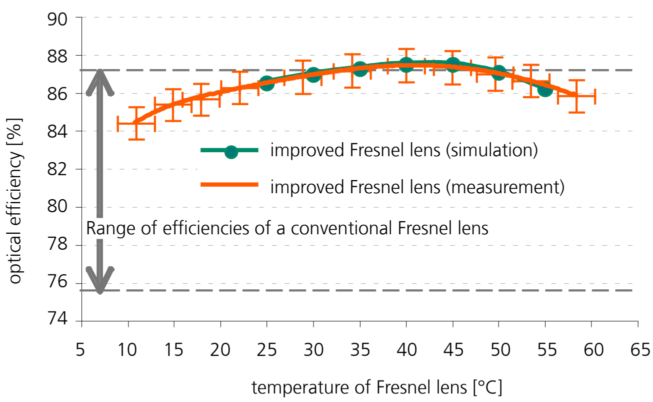
Thorsten Hornung, Peter Nitz, Werner Platzer

Most CPV systems apply Fresnel lenses to focus direct sunlight onto many small solar cells. Diffuse sunlight cannot be used in these systems. In addition, the system must track the sun mechanically. Thus, this highly efficient technology is most suitable for solar power plants in desert regions. The optical components are subjected to the strongly fluctuating temperatures at the location of the power plant.

Over the past years, we have improved and extended our specialised measurement facilities for concentrator optics. In parallel, we have further refined computer simulations of the optics and integrated various temperature effects. Our measurements show that the Fresnel lenses used do not function equally well at all temperatures. As a result, sometimes several percent of the incident radiation is lost for electricity generation in power plants. With the help of our computer models, we developed Fresnel lenses which have weaker temperature dependence than conventional concentrator Fresnel lenses in the relevant temperature range between 10 °C and 60 °C (Fig. 2). Measurements of prototypes of these lenses agree very accurately with the results which we predicted on the basis of our computer models.

We are thus confident that these improved Fresnel lenses will also deflect significantly more light on average onto the solar cells, which can then be converted there into electricity. In this way, the system efficiency will increase and the cost of the generated electricity will decrease.

1 *Glass pane with Fresnel lenses for concentrating photovoltaics. Numerous lenses are closely packed over the surface of the pane. After mounting in a concentrator PV module, a tiny solar cell is located at the focus of each lens. The lighting situation for the photo is different to that in a real module.*



2 *Optical efficiency of the newly developed Fresnel lens with weaker temperature dependence. The efficiency predicted by simulation is confirmed by the measurement results. Measurements of a conventional Fresnel lens reveal a much greater variation in the optical efficiency, which is lower than that of the newly developed Fresnel lens at almost all temperatures.*

HEATING, COOLING AND ELECTRICITY FROM THE SUN

SOLAR THERMAL TECHNOLOGY

Solar thermal systems with different operating temperatures find their application in HVAC technology in residential and commercial buildings, in industry or as large-area, ground-based solar arrays. The heat generated from solar energy can either be used directly or converted via thermal power plants into electricity or by thermal chillers into cooling power. In general, the two decisive factors for system performance are the optical efficiency and the reduction of thermal losses.

The market for "Solar Thermal Technology" ranges from low-temperature to high-temperature applications: solar-thermal collectors and collector systems based on different types of flat-plate and evacuated tubular collectors have multi-facetted applications ranging from domestic hot water and solar-assisted space heating systems, through cooling and air-conditioning, to desalination units suitable for use with seawater. Façade-integrated collectors and window-mounted collectors are also used. Operating temperatures ranging from 150 °C to 550 °C can be reached with linearly concentrating collectors. Both parabolic trough and Fresnel collectors are used not only in large power stations for solar-thermal electricity generation, but also in often simpler and less expensive variants to generate process heat, process steam and driving heat for absorption chillers.

Solar-thermal energy systems convert solar energy into heat. Depending on the design of the solar-thermal collectors, the temperature increase above ambient temperature can vary from only a few degrees to several hundred degrees. The lower the thermal losses of a receiver, the better the optical efficiency values and the higher the concentration factor for the radiation, the higher are the possible operating temperatures. Optical surfaces and materials are important for implementing efficient systems. This is the link to the business unit addressing "Applied Optics and Functional Surfaces".

We have developed selective absorber coatings for solar-thermal collectors (temperatures of up to 230 °C) and transferred them to industrial production for many years now. However, coatings for absorber pipes in solar-thermal power plants may permanently have to withstand much higher temperatures (up to 650 °C for tower receivers). This is achieved by integrating additional layers into the coating stack to act as diffusion barriers, selected according to the type of absorber pipe.

The efficiency of a collector, however, does not depend on its surface properties alone, because the fluid dynamic properties and heat transport within the collector are also decisive parameters. A homogeneous flow distribution combined with a low pressure loss in flat-plate collectors is achieved with our FracTherm® concept, which is based on bionic principles. Completely new design and manufacturing options for solar-thermal collectors have been opened up by applying this approach. We are investigating alternative collector materials to aluminium and copper, e.g. steel, but also non-metallic materials.

Open, sorption-assisted air-conditioning processes can be operated efficiently with simple flat-plate collectors. They allow the temperature and relative humidity of inlet air to be conditioned as required. Some other thermal cooling processes demand higher operating temperatures. For this reason, concentrator collectors are also being developed and applied to optimise the complete system.

In countries with a high proportion of direct solar radiation, solar-thermal power stations offer enormous potential to generate electricity inexpensively, both for the daily peak load and for longer periods with higher loads. Steam is generated at high temperatures and drives the turbine as in a conventional power station. This means that solar collector fields can be integrated simply into hybrid power stations, which convert other sources of heat in addition to solar energy. With this approach, the power stations can supply electricity around the clock. Non-solar heat can be supplied regeneratively e.g. from biomass. Hybrid energy sources or heat storage can enable the power stations to supply electricity even at night. In general, the concept of solar power plants is associated with

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large projects in the 20–400 MW_{el} range. However, we are also investigating the opportunities for medium-sized solar-thermal systems on an industrial scale. Their economic feasibility can be clearly improved by heat and power (and cooling power) cogeneration and simpler operating conditions.

Fraunhofer ISE is competent in all fields relevant to thermal applications of solar energy, ranging from materials science, component design, testing and measurement procedures, theoretical modelling and simulation up to systems controls and systems technology for the different applications.

Special facilities:
- vacuum deposition system for quasi-industrial production of complex absorber and reflector prototypes on flat and curved surfaces and tubes (140 x 180 cm^2)
- measurement technology (REM, Auger, EDX) applying materials science to investigate changes in the coatings due to thermal or other loads
- optical measurement technology: spectrometry, goniometry, luminance measurements with imaging methods, fringe reflectometry, special measurement facilities for concentrating optics
- thermal technological laboratory to measure the performance and transient behaviour of thermal power generators (up to 50 kW_{el}) and high-temperature storage units
- testing laboratory to test the performance of membrane distillation systems and the stability of components to seawater exposure
- TestLab Solar Thermal Systems: certified solar-thermal testing laboratory for collectors and systems according to the Solar Keymark (performance and authorisation tests, outdoor and indoor testing, temperature measurement of heat-transfer media up to 200 °C), also suitable for measuring solar air collectors

In countries with a high proportion of direct solar radiation, solar-thermal power plants possess enormous potential to generate solar electricity inexpensively and flexibly for the daily peak demand and periods with higher loads. Fraunhofer ISE addresses not only the optimisation of optical surfaces and materials but also Fresnel concepts and corresponding adaptation of reflectors for the collector arrays. Another focus is the development of novel storage concepts for latent heat with phase change materials, so that electricity can be generated independently of the prevailing solar radiation conditions.

CONTACTS

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SOLAR PROCESS HEAT: SYSTEM MONITORING AND PLANNING AIDS

Industrial process heat accounts for about 44 % of the heat demand in the European Union (EU), so causes more than 20 % of our total end energy demand. Solar thermal systems have the potential to supply app. 10 % of the European demand for process heat at temperatures below 250 °C. We have monitored a pilot solar-thermal plant in detail, which supports the steam network of a commercial laundry, and used the results to validate the yield simulations for a flat-plate collector for process heat that we had developed. In an EU-funded project, we have identified four industrial processes with high potential and prepared system concepts and design nomograms for these applications.

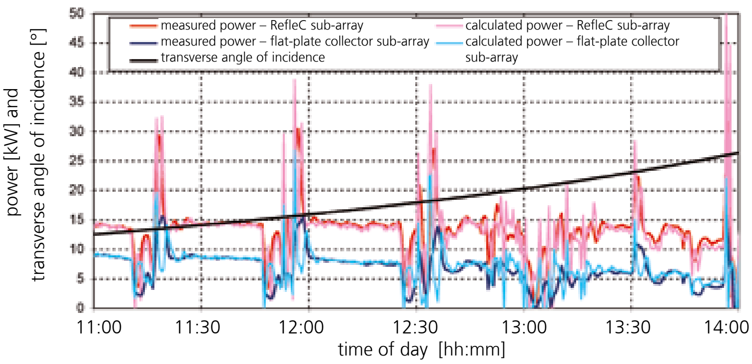
Michael Hermann, **Stefan Heß**, Paolo Di Lauro, Axel Oliva, Gerhard Stryi-Hipp, Werner Platzer

The RefleC collector (Fig. 1), which was developed by Fraunhofer ISE in co-operation with the Wagner & Co. Solartechnik company, is used in the pilot system, operating at 6 bar and up to 130 °C. A cascade of storage tanks (Fig. 2) pre-heats make-up water for steam-generating boilers up to 90 °C and boiler feed water up to 120 °C. Furthermore, hot water is provided at 60 °C for the washing machines.

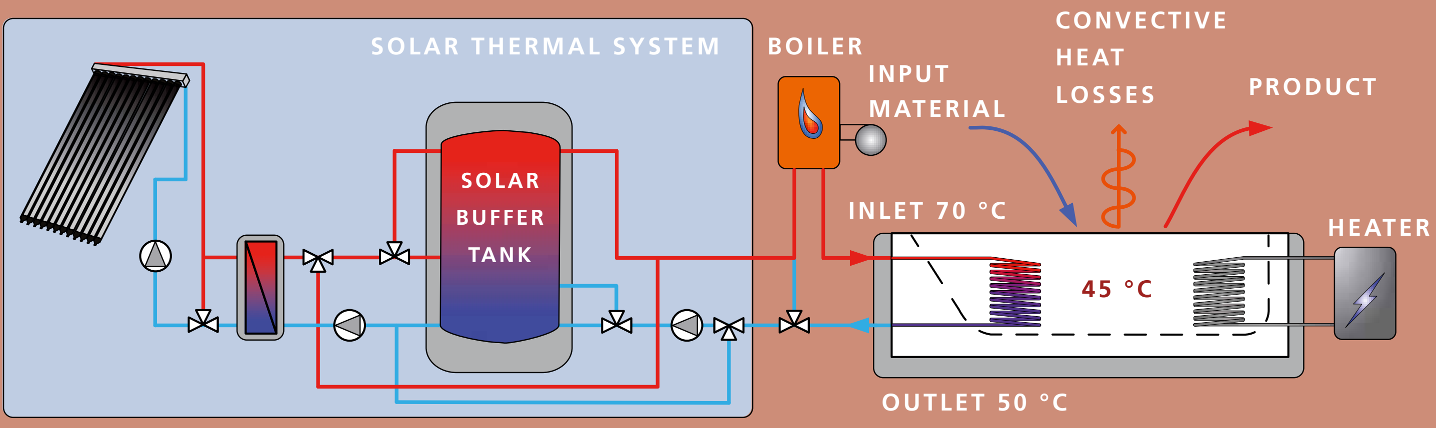
In Fig. 3 we have compared the actual measured instantaneous power of the RefleC collector array and a reference collector array (without reflectors) with the calculated values. The basis for the power calculations are the collector efficiency characteristics as measured in "TestLab Solar Thermal Systems", the incidence angle modifier (IAM) values determined for the two collector arrays by ray-tracing simulations and the values measured for the pilot plant (radiation intensity, inlet and outlet temperatures and mass flow rates). It is evident that the RefleC collector delivers several times the power of the reference collector as the transverse angle of incidence increases (angular component in the plane perpendicular to the reflectors). The power increases for outlet temperatures exceeding 120 °C and a transverse angle of incidence of 27 °C to almost three times the reference value (Fig. 3, 13:50). The calculated power agrees very well with the measured values; the entire collector array and the individual sub-arrays thus operate with the theoretically predicted performance.

1 Collector array of the Laguna laundry in Marburg, Germany. The RefleC collector trough (two sub-arrays) is constructed as a double-glazed (glass and plastic film) flat-plate collector with an external reflector. This reflector supports the row in front, which is also double-glazed, but without a reflector (one sub-array).

2 Cascaded tanks of the pilot plant (pressurised at 2 bar). The tank charging is controlled by the red three-way valves between the primary storage tank (left hand side, 1 m³, T_{max} = 120 °C) and the secondary storage tanks (right hand side, 2 x 1 m³, T_{max} = 110 °C).



3 Comparison of measured and calculated instantaneous power of the RefleC collector and the double-glazed flat-plate collector in front on Saturday, 21st August 2010.



4

Analysis of the monitoring data reveals that the RefleC collector achieves app. 89 % higher yields than the reference collector without reflectors for inlet temperatures above 80 °C. The solar fraction for the assisted processes amounted to 15 %. The solar system and better scheduling of the heat demand by the laundry meant that one of the gas-fuelled boilers could be switched off completely, which resulted in load-corrected gas savings of 8 %.

4 *System concept for solar heating of a galvanic bath.*

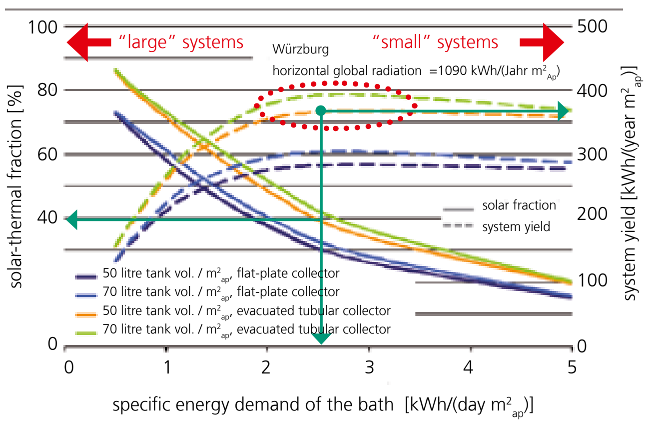
In the IEE-funded "SO-PRO" project (Solar Process Heat), we supported six European regions in market development for solar process heat. Based on regional surveys and screening of 60 industrial enterprises, four processes were identified for integrating solar energy:

- heating water for washing or cleaning purposes
- heating make-up water for the boilers supplying steam networks
- heating of processing baths or containers
- convective drying with hot air

We have developed typical load profiles and examples of system concepts for each of these processes (Fig. 4). TRNSYS simulations were then used to prepare design nomograms for the six European regions for preliminary dimensioning (Fig. 5). A planning guide (SO-PRO Design Guide) includes not only these results but also an integrated planning approach for solar process heat. We have disseminated the tools developed in the IEE-funded "SO-PRO" project to solar companies, process planners and energy consultants in numerous regional and international training seminars.

Our work on collector development and monitoring was supported within the "Solarthermie2000plus" Programme. Preparation of the planning aids and conduction of the training seminars was financed by the EU.

www.solar-process-heat.eu
www.solar-process-heat.eu/guide

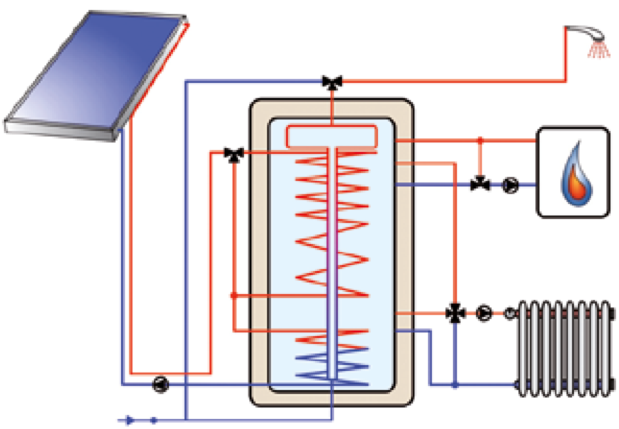


5 *Design nomogram based on parameter variations in simulations of the system shown in Figure 4 (operation between 6 a.m. and 10 p.m., reduction of energy demand by 80 % during the night and at weekends, no company holidays, collector tilt 35°, south orientation). The red oval identifies promising designs.*

SOLAR-ACTIVE HOUSE – HEATING WITH A HIGH SOLAR FRACTION

Solar heating systems, which support not only domestic hot water but also space heating, are installed today in Germany on a regular basis. These typically supply about 25 % of the total heating demand of a well-insulated free-standing house. However, the vision of the German and the European solar-thermal technology platform is a building with 100 % solar-thermal heating. As an intermediate step, increasing numbers of so-called solar-active houses are being built, in which 50 to 100 % of the total heating demand is met by thermal solar energy. Fraunhofer ISE is investigating this heating concept with the goal of evaluating its functionality in existing buildings, identifying its potential for optimisation and making the heating concept comparable with other zero-energy building concepts.

Axel Oliva, **Gerhard Stryi-Hipp**, Werner Platzer



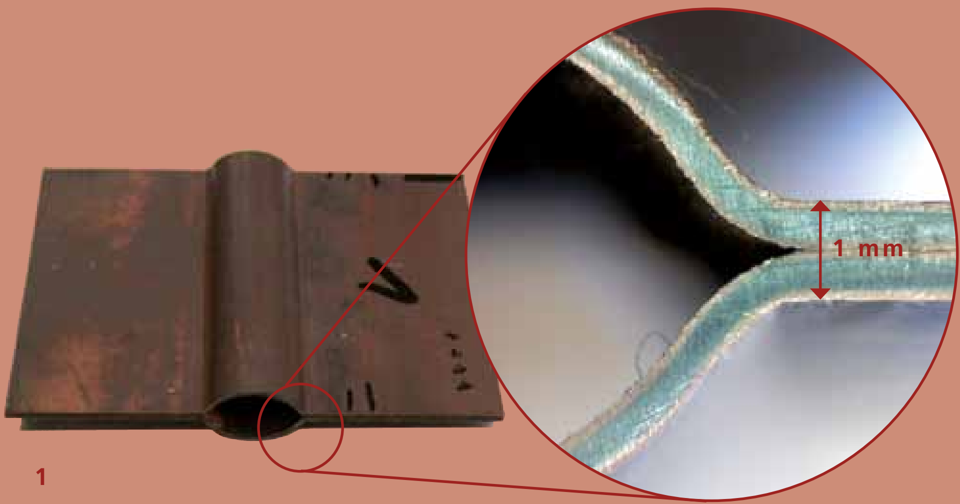
2 *Typical layout of a solar thermal system with a high solar fraction.*

1 *The "Solar Office Seebronn" will be measured within the "HeizSolar" project.*

About 1000 solar-active houses with a solar fraction between 50 and 100 % have been built so far. These are usually free-standing houses with improved thermal insulation with a specific transmission heat loss between 0.2 and 0.3 W/(m²K), a solar collector area between 30 and 60 m² and a water tank with a volume between 6 and 10 m³ for heat storage. High solar fractions require seasonal storage of some of the solar-generated heat from summer into the heating season. A significant share of the solar heat is also generated during the heating season by solar collectors which are mounted at a steep tilt angle and oriented to the south. The optimum concerning heat losses, solar gains and seasonal storage needs to be found for the solar-active house under these conditions.

In the "HeizSolar" project, Fraunhofer ISE is co-operating with Solar- und Wärmetechnik Stuttgart, the Technical University of Ilmenau and the Sonnenhaus Institute to evaluate the concept of solar-active houses, with the aim of assessing and optimising them. To this purpose, currently nine typical solar-active houses are being monitored to determine their functionality in practice and determine the solar fractions that are actually achieved. A simulation model is being prepared for the buildings and validated with the measured data. The optimisation potential for the solar heating concept is being identified on the basis of variant analysis. A concept for comparative evaluation of the solar heating concept with respect to other low-emission building concepts should allow the potential of solar-active houses to be estimated.

The "HeizSolar" project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and the Projektträger Jülich (PTJ).



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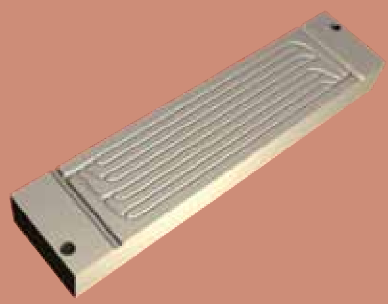


2

STEEL ABSORBERS BASED ON ROLL-BONDED, HYBRID SEMI-FINISHED PRODUCTS

The absorber represents the largest cost factor in solar-thermal collectors. In order to reduce these costs, we are co-operating with the Institute of Forming Technology and Lightweight Construction (IUL, Technical University of Dortmund) to investigate the possibilities of substantially replacing the previously applied metals of aluminium and copper with less expensive steel, on the one hand, and to test a manufacturing process for mass production of solar absorbers, on the other hand. The investigated process combines partial cold roll-bonding with internal high-pressure forming. It offers the possibility to manufacture very flexible channel structures, so that we were able to design a configuration implementing varying channel heights and the bionic FracTherm® structures that we have developed.

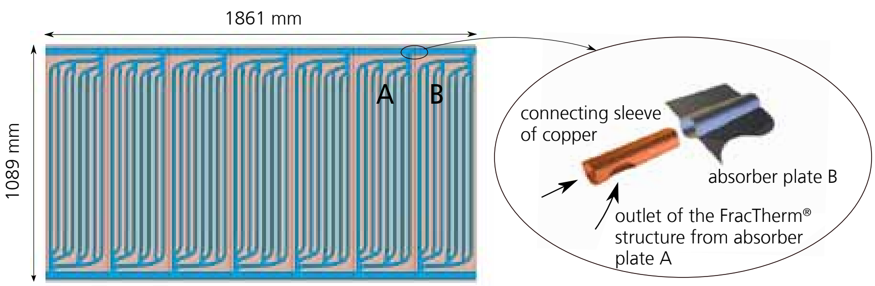
Max Bauch, Wolfgang Graf, Michael Hermann, Michael Klemke, **Lotta Koch**, Werner Platzer

The solar-thermal absorber developed at Fraunhofer ISE consists of a bonded stack of two steel plates, which were plated on both sides with a thin copper layer (a few hundredths of a millimetre) in an initial rolling step (Fig. 1). After a separating agent has been deposited onto the preliminary copper-steel-copper composite plate, this is pressed onto a second preliminary composite plate in a further rolling step. This partially cold roll-bonded composite is then formed in a mould (Fig. 2) and equipped with fittings. The process is similar to roll-bonding but is more flexible regarding both the choice of materials and the design possibilities for the channels. In order to achieve a high collector efficiency factor F´ simultaneously with low pressure losses, we varied the cross-sectional form in simulation studies. To do so, we adapted the existing models for F´ and pressure loss, and carried out initial measurements with our fluid dynamics test rig to validate the models and determine empirical correction factors. The channel structure was designed with the so-called FracTherm® algorithm, which aims to achieve homogeneous flow through the entire collector and low pressure losses. With the manufacturing process described above, an absorber with a quasi-fractal channel structure (6 mm high) and collection channels with a larger cross-section (20 mm high) can be produced in a single step for the first time. For manufacturing reasons, a modular absorber concept was developed with copper sleeves as the connectors (Fig. 3).

1 Demonstrator channel and a detail to illustrate the copper-steel-copper layer configuration. This stack guarantees internal/external protection against corrosion by the solar fluid and the environment, and provides a good substrate for a selective absorber coating.

2 CAD model for the mould used in internal high-pressure forming.

The project was managed by the Institute of Forming Technology and Lightweight Construction (IUL) of the Technical University Dortmund and supported by the Forschungsvereinigung Stahlanwendung e. V. (FOSTA).

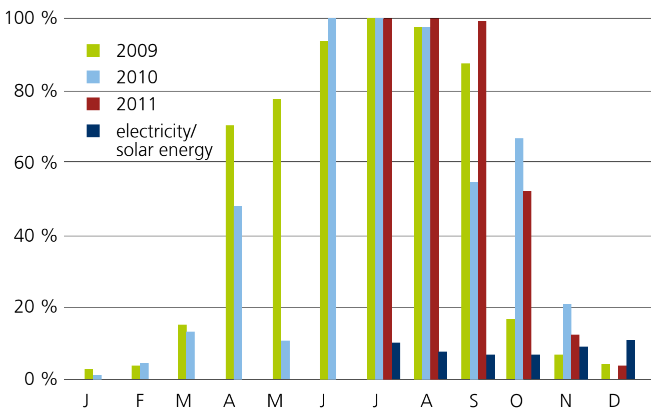


3 The illustrated modular absorber concept offers the possibility for very flexible absorber and thus also collector dimensions.

HIGHLY EFFICIENT SOLAR AIR-HEATING COLLECTORS TO ASSIST SPACE HEATING

High air temperatures can be achieved efficiently with the evacuated tubular solar air-heating collector that was developed by the Kollektorfabrik GmbH & Co. KG. The heated air can be used directly for thermal processes or in air-conditioning and ventilation systems. However, if an additional air-water heat exchanger is installed, stagnation-proof, large-area solar systems can also be implemented for solar-assisted space heating and domestic hot water, due to the high usable temperature level. A field test with seven demonstration systems is intended to clarify how well the collector is suited for this application – also with regard to the parasitic electricity demand for the fan.

Korbinian Kramer, Gerhard Stryi-Hipp, **Christoph Thoma**, Werner Platzer



1 *Three evacuated tubular solar air-heating collectors with a total collector gross area of 27.5 m². The horizontal air duct in the centre of the collector array gathers the heated air. A heat-exchanger unit, which was developed for these collectors and consists of a fan and heat exchanger, is installed on the roof next to the collector array.*

Good heat transfer from the air to water or a water-glycol mixture with low pressure losses is an important property for these systems. A heat-exchanger unit with a heat exchanger and a fan was developed as part of the project. The fan features a speed-controlled, energy-saving motor with low power consumption.

An inexpensive variant for the measurement technology to monitor the collector was tested, which can also provide data to the solar controller. The measurement equipment was calibrated in the laboratory before its application in the field. However, frequent sensor defects indicated that this measurement technology is not adequate for accurate measurements. For this reason, hiqh-quality measurement technology has been installed additionally in two systems to allow accurate evaluation.

The project is supported by the Deutsche Bundesstiftung Umwelt (DBU).

2 *Monthly solar fractions for the solar system. Operation in 2009 and 2010 was used to optimise the solar system. High-quality measurement technology has been installed since July 2011. The ratio of driving energy to output energy is shown in violet for 2011. In July 2012, the measurement period with the high-quality measurement technology will be concluded and the characteristic data for the system will be evaluated.*

1

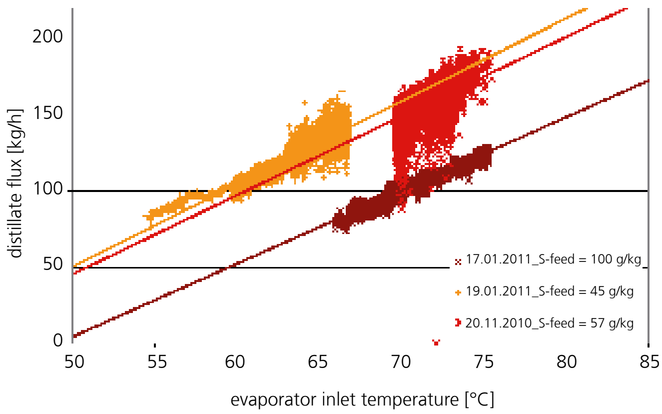
OPERATING EXPERIENCE WITH MEMBRANE DISTILLATION SYSTEMS

About 70 million m³ of drinking water are provided daily around the world by treating seawater and brackish water. However, remote regions with little infrastructure do not profit from the large-scale technology applied. Small, autonomously operating desalination systems must be developed for these applications. In arid and semi-arid regions, powering the systems with solar energy is an excellent option due to the prevailing meteorological conditions. At Fraunhofer ISE, we develop thermally driven membrane distillation systems which are able to prepare drinking water from seawater or brackish water, and which can achieve complete energy autonomy by operating with thermal solar energy or waste heat.

David Düver, Florian Groß, Mario Hillebrand, **Joachim Koschikowski**, Martin Rolletschek, Daniel Pfeiffle, Rebecca Schwantes, Marcel Wieghaus*, Daniel Winter, Werner Platzer

* SolarSpring GmbH

1 Membrane distillation system on Gran Canaria – 12 MD modules, 190 m² collector area and 7 m³ thermal storage capacity for night operation. The system has been operating since early in 2011 and produces up to 200 l/h. The desalination system and essential components of the hydraulic system are installed in a 20 ft container.



2 Experimental determination of the distillate flux as a function of the evaporator inlet temperature for the desalination plant on Pantelleria (Italy).

Membrane distillation (MD) is a thermal separation process, in which evaporation from a sol occurs through a membrane. The liquid sol is held back by the membrane. A temperature difference between the two sides of the membrane must be established as the driving force. At Fraunhofer ISE, we develop and implement MD modules, systems and pilot plants for desalination of seawater and brackish water. We have developed simulation models for dimensioning, which we have validated using test rigs in the laboratory for a very wide range of operating conditions. To produce the desalination modules, we are equipped with the necessary machines, allowing us to tune the modules to the particular application.

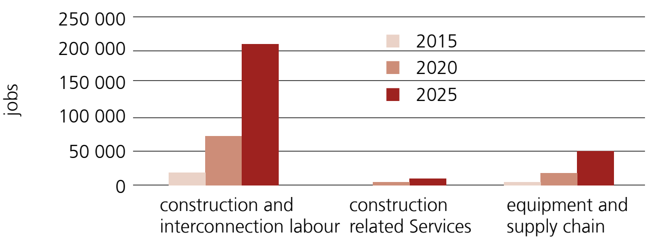
Within the EU-funded "MEDIRAS" project, we have installed two desalination plants that are powered by solar energy and waste heat and have nominal daily outputs of 3.5 and 5 m³ respectively, on Gran Canaria and Pantelleria. A further solar-powered system was taken into operation in North Namibia with support from the German Federal Ministry of Education and Research (BMBF) within the "CUVEWATERS 2010" project. The results from operation agree well with the values from the dimensioning simulations. The influence of the upper operating temperature and the salt content on the distillation power was investigated (Fig. 2). During operation in Namibia, extensive tests on scaling caused by calcium deposits were carried out and countermeasures such as flushing cycles with acid were developed and tested.

SOLAR-THERMAL POWER STATIONS – A GAIN FOR ALL CONCERNED

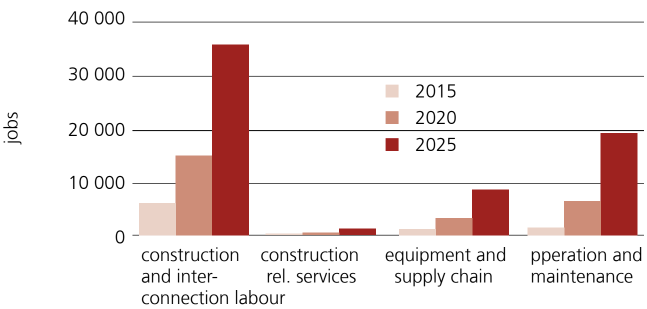
Major expansion in the global capacity of solar-thermal power stations is to be expected. To date, most concentrated solar power (CSP) stations have been constructed in southern Europe and the USA, although the Middle East and North Africa (MENA) present the greatest application potential worldwide and thus the best opportunities for this technology. The region could profit greatly economically by expanding its CSP capacity. The potential was investigated in a study co-ordinated by Fraunhofer ISE.

Christoph Kost, Gabriel Morin, Werner Platzer

1 *Andasol 1 solar-thermal parabolic trough power station in Spain.*



2 *Cumulative numbers of short-term jobs during the construction phase in the transformation scenario (expansion of CSP to 5 GW by 2020).*



3 *Number of jobs related to CSP in 2015, 2020 and 2025.*

The success and the acceptance of solar-thermal power stations in the five investigated countries (Egypt, Algeria, Jordan, Morocco and Tunisia) depend strongly on the integration and participation of local industry. Thus, it is important to assess the potential for participation by local industrial sectors.

The study entitled "MENA Assessment of Local Manufacturing Potential for Concentrated Solar Power (CSP) Projects" was prepared by the Fraunhofer Institute for Solar Energy Systems ISE and the Fraunhofer Institute for Systems and Innovation Research ISI in co-operation with Ernst & Young. In collaboration with industrial partners in North Africa and Europe, we analysed the CSP value chain, the production processes for the key components of a solar-thermal power station and the industrial potential in the MENA countries. Our study is based on an analysis of the technological demands of the various production processes, ranging from simple construction activity (e.g. foundations) to the manufacture of specialised components (e.g. evacuated receiver). We also investigated the structure and capabilities of companies in the MENA countries. Depending on the focus of industrial activities and the regional market development, the local economy can become integrated to varying degrees. On average, the local financial benefit of CSP power stations in the MENA region can reach up to 60 %, which corresponds to 14.3 thousand million US dollars. By 2025, 60 000 to 80 000 new, permanent jobs, some of them highly qualified, could be created in the MENA region. In this way, the countries would profit from establishing production capacity and extensive infrastructural development projects for renewable energy if they exploit their regional advantages and remove market barriers. European system manufacturers and component suppliers also see major medium-term growth opportunities in this market. Europe and MENA could thus both benefit from new markets due to the enormous potential for solar electricity in the region.

HIGH-TEMPERATURE STORAGE CONCEPT WITH PHASE-CHANGE MATERIALS

Efficient thermal storage units which can be charged and discharged by steam are needed so that solar collectors for direct steam generation can provide energy independently of the prevailing amount of solar radiation. Phase-change storage units are very suitable for this purpose. Due to technical hurdles, e.g. the low thermal conductivity of the materials, there are not any latent-heat storage products on the market at present. We are developing a novel concept for storage of latent heat, in which the phase change occurs in a spiral heat exchanger. This allows latent heat to be stored efficiently and economically. The feasibility of the concept has already been proven. We are now constructing a laboratory prototype which we will measure and optimise.

Stefan Gschwander, **Anton Neuhäuser**, Peter Nitz, Verena Zipf, Werner Platzer

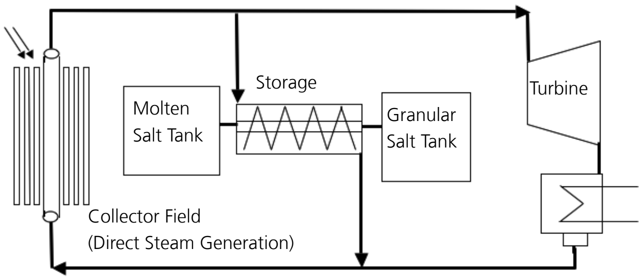
Direct steam generation in solar-thermal collectors enables high efficiency due to the elevated working temperature and avoidance of a second fluid circuit in the solar array. A storage unit is necessary in order to increase availability. It is not effective to use the conventional two tanks designed to store sensible heat for the charging and discharging of two-phase media such as water/steam, as they cause large exergy losses during the storage process. Instead, phase-change materials (PCM) are ideal with regard to exergy, as large temperature gradients during heat transfer are minimised due to their characteristic isothermal phase transition.

At present, the poor thermal conductivity of PCM has been a hurdle which has prevented the development of a commercially viable storage concept up to now, as it demands uneconomically large heat exchanger areas. In our novel concept, a spiral heat exchanger is used, which is charged and discharged with steam. The phase change occurs during transport along the heat exchanger surfaces and the material is subsequently stored in a separate tank. In this way, the storage capacity and the charging and discharging rates are decoupled from the area of the heat exchanger surface.

We are now setting up an experimental storage unit on a laboratory scale and equipping it with comprehensive measurement technology. It will be used to validate simulation programs by experimental series and to optimise the design of the storage unit.

Our development of an efficient and economic high-temperature storage unit is supported by the E.ON International Research Initiative.

1 *Double-axis spiral heat exchanger: a heat-transfer fluid flows through the hollow axis, the hollow vanes and the trough. The PCM melts/solidifies in the interior of the trough and is transported into a tank.*



2 *Concept for integrating the new high-temperature storage unit into a solar-thermal power station applying direct steam generation (process to charge the storage unit).*

ELECTRICITY FROM SUNLIGHT

SILICON PHOTOVOLTAICS

Photovoltaics has experienced a boom for several years, which has been accompanied by a strong cost reduction. In 2011, the global production of solar cells was around 27 GWp, which corresponds to a growth rate of 60 percent compared to 2010.

More than 85 percent of all PV modules sold are based on solar cells manufactured of crystalline silicon. The price-to-performance ratio, long-term stability and reliable predictions for further cost reduction indicate that this peak performer in terrestrial photovoltaics will continue to dominate the market in the future. Our R&D activities aim to further advance the cost degression for this type of solar cell and cover the complete value chain for crystalline silicon photovoltaics.

In the Silicon Material Technology and Evaluation Centre SIMTEC, we work on high-throughput epitaxial production of silicon films, and the development of block-crystallised silicon. For block crystallisation, we are equipped with a crystallisation facility, where multicrystalline blocks weighing 15 kg to 250 kg can be produced. Sawing and polishing technology is available, so that we can produce columns and wafers from the crystallised blocks. Our scientific work here focuses on improving the crystallisation process to produce silicon crystals as the starting point for highly efficient solar cells, and adapting the crystallisation processes to each particular type of solar silicon, e.g. upgraded metallurgical grade (UMG) silicon.

The concept of the crystalline silicon thin-film solar cell combines very high-quality crystalline films with methods from thin-film solar cell production, such that it can potentially achieve very low costs for PV modules. We are developing specific facilities and processes for this concept. Our work is focussed mainly on equipment for high-throughput silicon deposition and zone-melting recrystallisation, as well as appropriate processes to produce substrates, films and solar cells. The vertical integration of our work from the substrate to the sub-module with its integrated circuit means that we can tailor the individual steps to each other. We have excellent boundary conditions to reach our goals with a laboratory area of 1000 m² in SIMTEC and in specialised laboratories for crystallisation, wet chemistry, solar cell processing and characterisation.

A central activity of our ETAlab® is the development and analysis of high-efficiency solar cell concepts and processes. The goal is to achieve higher efficiency values with cost-effective processes and thus provide the pre-requisite for substantial cost reduction in silicon photovoltaics. ETA in the laboratory name stands for Efficiency, Technology and Analysis. Among the various solar cell concepts that currently exist, we are focussing particularly on back-contacted cells and structures for n-type silicon. ETAlab® is equipped with excellent processing infrastructure in a clean-room laboratory with a floor area of 500 m², which has allowed us to set several international records for efficiency. In addition, further laboratory area of 900 m² is available for us to develop effective surface passivation methods, novel metallisation and doping techniques, innovative nano-structuring technology and new characterisation methods.

In our Photovoltaic Technology Evaluation Centre PV-TEC with an area of more than 1200 m², we can produce both solar cells with screen-printed contacts, as are common in industry, and also solar cells with high-quality surface passivation on a pilot scale, i.e. with a throughput of more than 100 wafers per hour. For the various types of processing technology, both flexible, semi-automatic equipment and high-rate, fully automatic systems for process development are available. Our development of production-relevant technology for crystalline silicon photovoltaics is concentrating on high-temperature and printing technology, wet chemical and plasma chemical processes, as well as laser and physical vapour deposition. These technological facilities are complemented by in-line and off-line measurement instrumentation. All material and processing data are stored in a central data bank, guaranteeing that our high quality specifications are met, which makes them particularly suitable for analysing new materials. Our

activities range from development of new concepts at the pilot stage, through evaluation of new technology, to transfer to the production lines of our co-operation partners.

For all of the technological foci mentioned above, our excellent characterisation and simulation pool provides the foundation for effective and scientifically based development. We are playing a leading role in the development of new characterisation procedures such as the imaging photo-luminescence method to analyse silicon material and cells.

Finally, the Photovoltaic Module Technology Centre MTC at Fraunhofer ISE allows new cells and materials to be processed in industrially relevant quantities and formats. Processing steps and systems technology for module production are developed up to the preliminary stage of mass production. The core equipment includes a flexibly applicable tabber-stringer and a laminator, accompanied by a selection of measurement and testing systems. Further details about these activities can be found in the chapter on photovoltaic modules and systems (see page 82 ff).

Our activities on silicon material and solar cells in Freiburg are complemented by the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen (see page 65), the Technology Centre for Semiconductor Materials THM in Freiberg, saxony, which is operated jointly with Fraunhofer IISB, and the Centre for Silicon Photovoltaics CSP in Halle, which is operated jointly with Fraunhofer IWM (see page 12).

In the Silicon Material Technology and Evaluation Centre SIMTEC, we are optimising the quality of block-crystallised silicon. The Centre is equipped with a crystallisation facility to produce multicrystalline blocks with a mass of 15 kg to 250 kg, and also sawing and polishing technology to manufacture wafers. Scientific research there is focussing on improving the crystallisation process to produce high-quality silicon crystals as a basis for solar cells with the highest efficiency, and adaptation of the crystallisation processes to specific types of solar silicon, e.g. upgraded metallurgical grade silicon (UMG).

CONTACTS

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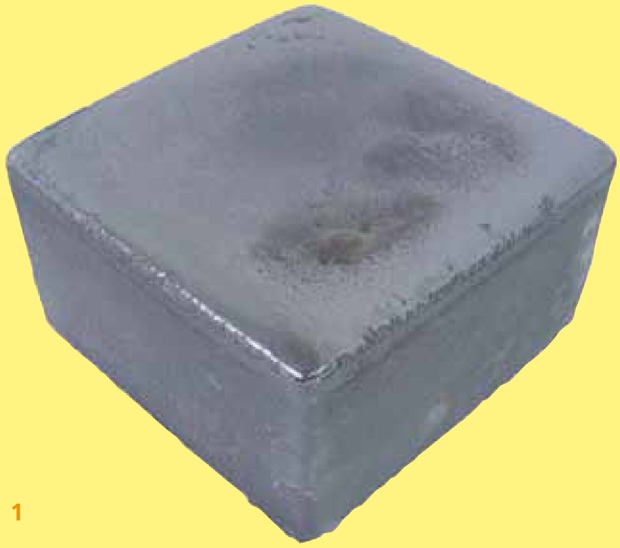

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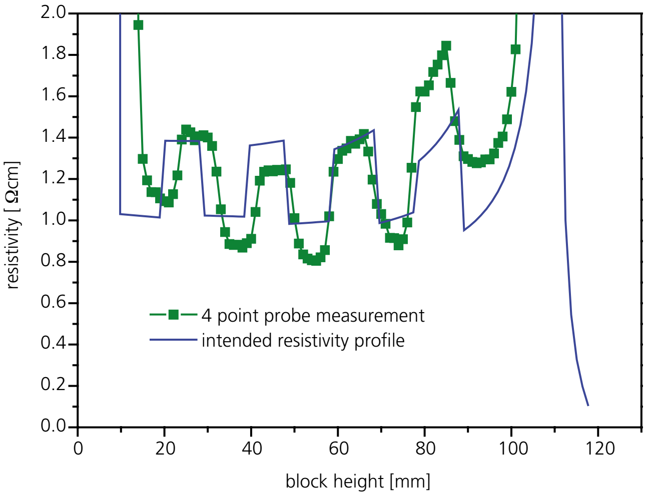
2

DOPING ENGINEERING FOR MULTICRYSTALLINE BLOCK SILICON

The use of alternative silicon materials to produce silicon blocks is a focus of our work at the Silicon Material Technology and Evaluation Centre SIMTEC belonging to Fraunhofer ISE. We have developed the method of so-called doping engineering to allow cost-effective upgraded metallurgical grade silicon to be used in industrial production. In this method, the electric resistance is adapted to the chemical properties of the feedstock material via the block height. In this way, we can significantly improve the yield from a silicon block in comparison to conventional procedures. The material properties are analysed either directly for the as-cut crystal or for the finished wafer after the wire-sawing process at SIMTEC.

Alban Brettmeister, Fridolin Haas, **Stephan Riepe**, Claudia Schmid, Mark Schumann, Andreas W. Bett



3 *Resistance distribution over the block height of a G1 test block, measured with the 4-point method. The blue line shows the resistance profile which was planned as part of the process development.*

1 *Multicrystalline block in the G1 research format (15 kg silicon).*

2 *Photoluminescence (PL) image of the cross-section of a G1 test block to analyse doping engineering. The step-wise addition of dopants at different heights causes the differences in the PL signal which are evident as striations.*

In the development of upgraded metallurgical grade silicon (UMG-Si) as an inexpensive alternative to conventional silicon feedstock, achievement of homogeneous electrical resistance over the entire height of the crystallised block is a great challenge to industrial production and thus to successful market introduction. The specific feature of this feedstock is that boron and phosphorus impurities are present in similar quantities. In standard crystallisation processes, this results in sometimes quite large yield losses due to conversion from p-type to n-type in the upper region of the block. As part of our research on this material, we are thus investigating how we can manipulate the incorporation of boron and phosphorus as dopants in the block. We simulate the crystallisation process with the commercial CGSim software and validate the models with experiments to determine the crystallisation rate and the phase front between the crystal and the melt during the solidification process. By adding dopants stepwise, so-called doping engineering, we are now able to adjust the electrical resistance to the desired range. By choosing the amount of material and time for the additional doping appropriately, we have succeeded in almost completely avoiding pn conversion (Fig. 2). The yield increases as a result to similar values as for uncompensated silicon blocks. In further research we will optimise this process with regard to the solar cell efficiency values which can be achieved.

The project is supported by the Fraunhofer-Stiftung.

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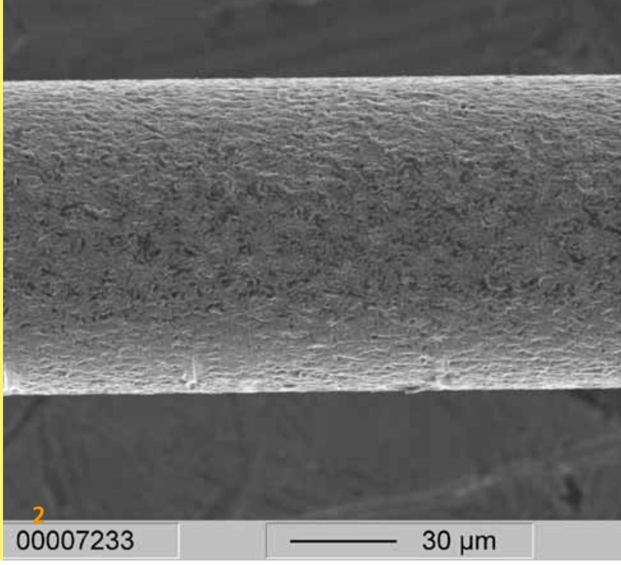


2

WIRE-SAWING PROCESS DEVELOPMENT FOR WAFER PRODUCTION

Wire-sawing is the dominant technology for producing silicon wafers for photovoltaics. The process is based on feeding a silicon block through a field of several hundred wire loops, with which the silicon material is sawn into wafers. At the Silicon Material Technology and Evaluation Centre SIMTEC, one focus of our work is further development of the wire-sawing process. In order to protect the process better against wire breakage during sawing, we investigated the wear of the wire during test sawing under industrially relevant processing conditions. The results show that the wire diameter decreases constantly with the sawing history of the wire, regardless of the initial diameter.

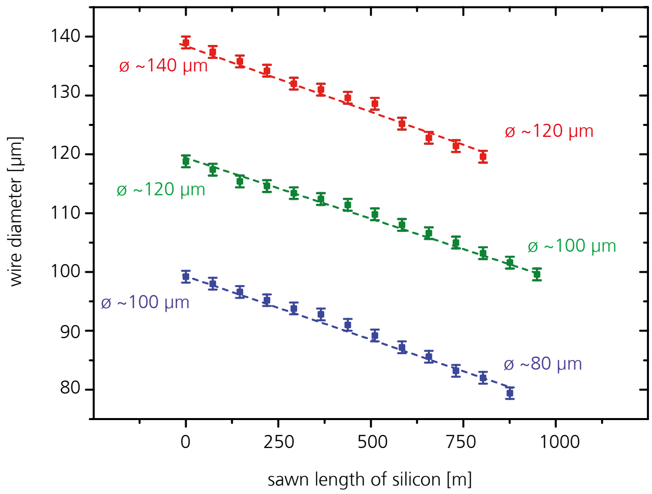
Philipp Häuber, Teresa Orellana, Stephan Riepe, **Bernd Weber**, Andreas W. Bett

In the industrial wire-sawing process with multi-wire saws, increasingly thinner wires are being used to reduce the kerf losses in manufacturing wafers from the previously crystallised silicon. As a result, the risk of a wire breaking during the sawing process increases. At the same time, reducing the wire diameter also influences the wafer thickness, depending on the sawing progress and position within the block. As part of our process research to produce thinner wafers, we have thus investigated the effects of wire wear. To do so, we carried out sawing tests at SIMTEC using wires of differing diameter. In order to simulate industrial sawing wear, a defined length of wire was used many times until the initial wire diameter had been reduced by 20 µm. We quantified the reduction of the wire diameter by scanning electron microscopy (Fig. 2) for different processes. Figure 3 shows the change in the measured wire diameter as a function of the sawing history of the wire. All tested wires show a similar linear dependence of the wire wear for identical processing parameters, independent of the initial diameter. The description of the wire wear makes it possible to adapt the pitch of the wire guide rolls to the changing wire diameter for a defined process, so that constant wafer thickness can be achieved over large batch quantities.

The work was supported by the European Commission and the Fraunhofer-Stiftung.

1 *Wafers from a multicrystalline silicon block, prepared at SIMTEC in industrial quality.*

2 *Scanning electron micrograph of the surface of a steel wire after the wire-sawing process. The surface displays indentations from the silicon carbide grains. The wire diameter was reduced by the wire-sawing process from initially 100 µm to 80 µm.*

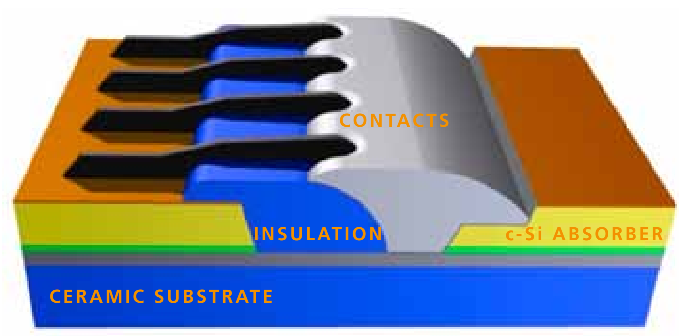


3 *Wire diameter of three different wires as a function of the sawn length of silicon. The change in the wire diameter is linear and independent of the initial wire diameter.*

CRYSTALLINE SILICON THIN-FILM SOLAR CELLS

Crystalline silicon thin-film solar cells represent a special type of crystalline silicon solar cells. They combine the positive characteristics of wafer solar cells and thin-film solar cells by achieving high efficiency with low silicon consumption. At present we are pursuing two concepts, wafer equivalents, in which the crystalline silicon thin-film solar cells are processed to a large extent with the highly developed process technology for wafer solar cells, and modules with integrated cell connection (IntegRex), which is very similar to classic thin-film technology. We address topics ranging from the substrate to solar cell processes that are specifically adapted for thin-film technology.

Björn Debowski, Elke Gust, Stefan Janz,
Miroslawa Kwiatkowska, Harald Lautenschlager,
Stefan Lindekugel, Regina Pavlovic, Thomas Rachow,
Stefan Reber, Kai Schillinger, Michaela Winterhalder,
Andreas W. Bett



2 *Schematic design of the thin-film module of recrystallised silicon with integrated cell connections (IntegRex). A ceramic substrate is encapsulated with a diffusion barrier layer of crystalline silicon carbide. The silicon absorber stack is deposited onto it and the cells are connected with an integrated circuit.*

1 *Zone-melted silicon layer (right) on a ceramic substrate which has been encapsulated by applying atmospheric pressure chemical vapour deposition (APCVD) (100 x 100 mm²).*

The central topics for crystalline silicon thin-film solar cells include not only substrate development but also the necessary functional layers and the specially adapted solar cell and module concepts. We made significant progress in all of these areas at Fraunhofer ISE. For example, we led a consortium of companies and research institutions in the development of a zirconium silicate ceramic, which is an ideal substrate for our IntegRex concept, from both an economic and a technological perspective.

In addition to successful production of zirconium silicate substrate samples, the consortium defined a virtual production line which could be implemented immediately. To encapsulate the substrates, we developed a vapour-deposited silicon carbide (SiC) coating, which effectively suppresses diffusion of impurities into the photovoltaically active Si layers. When selecting processes, we also pay particular attention to their scalability and cost-effectiveness. Thus, the preparation of the concept was accompanied by development of suitable equipment for film deposition and improvement of facilities to recrystallise Si films. We completed construction of the high-throughput ProConCVD facility, which is designed for the production of high-quality silicon and SiC films, and initial experiments have now started. Together with the ZMR400con zone recrystallisation system, we now have the complete range of equipment available to transfer the insights gained on small cell areas rapidly to production-relevant areas and to further improve the processes there.

The project was supported by the German Federal Ministry of Economics and Technology (BMWi).

LOW-TEMPERATURE THIN-FILM SILICON

In 2011, we established silicon thin-film technology at the Fraunhofer ISE Laboratory and Service Centre (LSC) in Gelsenkirchen. The first coating processes for amorphous and microcrystalline films were developed with the new three-chamber system. We have co-operated with industrial partners to develop a demonstrator which allows important structuring steps for thin-film technology to be carried out and optimised. Parallel to expanding the technological basis, we have extended the range of measurement technology such that individual layers as well as simple and multiple-junction cells can be characterised comprehensively.

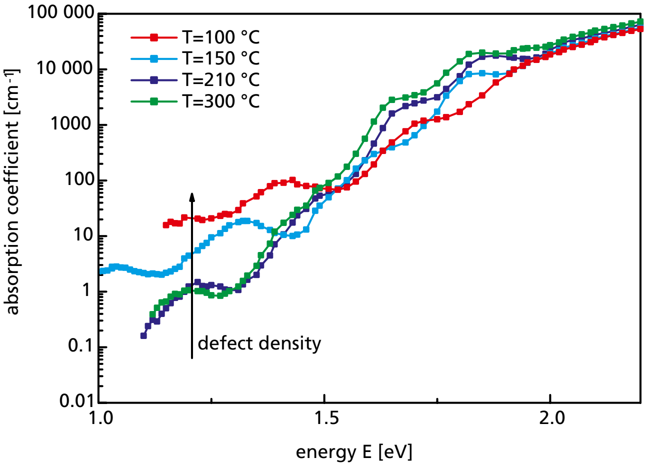
Dietmar Borchert, Martina Dörenthal, Stefan Hohage, Sinje Keipert-Colberg, Amada L. Montesdeoca-Santana, Markus Rinio, Petra Schäfer, Johannes Ziegler, Ralf Preu

Using our new three-chamber coating equipment (Fig. 1), we have developed initial standard processes for amorphous and microcrystalline Si films. We now achieve homogeneity of better than 3.5 % for all types of films over a coating area of 37 cm x 37 cm. The resulting films will be incorporated into simple and multiple-junction solar cells in future.

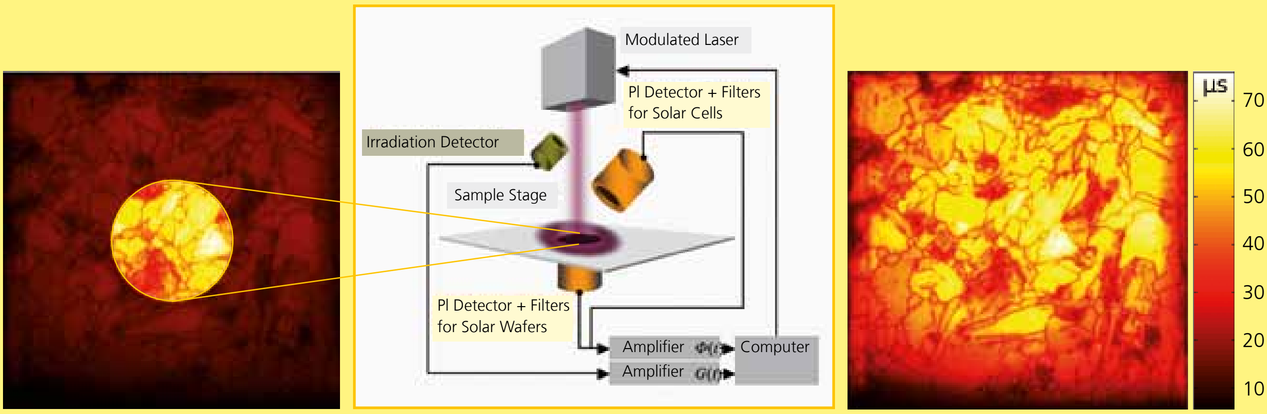
As part of the "ALPS" (Adapted Laser Processes for Silicon Solar Cells) research project, a demonstrator was developed, which we will use to test new laser systems and new beam profiles. Together with the large-area coating equipment, this system allows us to produce small modules with dimensions of 30 cm x 30 cm. Parallel to expanding our technological base, we have further extended our measurement technology to characterise thin films and solar cells. A central task involved setting up a measurement unit to determine the external quantum efficiency (EQE) of simple and tandem cells. By adding new hardware, we were also able to implement the CPM (Constant Photocurrent Method) with this unit. It allows the defect density in amorphous silicon to be determined, which is a direct indicator for the quality of the thin films (Fig. 2).

The "ALPS" project was supported by the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of the State of North Rhineland-Westphalia.

1 *New three-chamber coating system for the production of silicon thin-film solar cells.*



2 *CPM measurement of undoped amorphous Si films, which were deposited at different temperatures. The larger the absorption coefficient α at low energy values, the higher is the defect density in the material.*



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QUASI-STATIC LUMINESCENCE FOR ACCURATE LIFETIME MEASUREMENT

The charge carrier lifetime in silicon decisively influences the solar cell efficiency, so it is an important electrical material property for research and development as well as industrial process control in photovoltaics. Conventional methods to determine the lifetime can be subject to systematic errors – particularly for the new materials with relatively short lifetimes that are interesting for photovoltaics. Time-dependent measurement procedures based on luminescence, e.g. quasi-static luminescence, make it possible to avoid all known artefacts in lifetime measurements. At present, lifetimes down to a lower limit of 1 µs can be determined reliably for materials ranging from as-cut wafers through all stages of production to the finished solar cell.

Johannes A. Giesecke, Wilhelm Warta, Stefan Glunz

Efforts to reduce production costs for solar cells have considerably extended the spectrum of feedstock materials. Alternative methods to prepare material, e.g. from metallurgical grade silicon (both monocrystalline and multicrystalline) indicate a high potential for cost reduction. However, established measurement methods have currently reached their limits concerning reliable determination of charge carrier lifetimes, particularly in these new types of material. The reasons include trapped charge carriers, reliance on prior knowledge or measurability of dopant concentration and charge carrier mobility or optical artefacts caused by surface morphology and absorption.

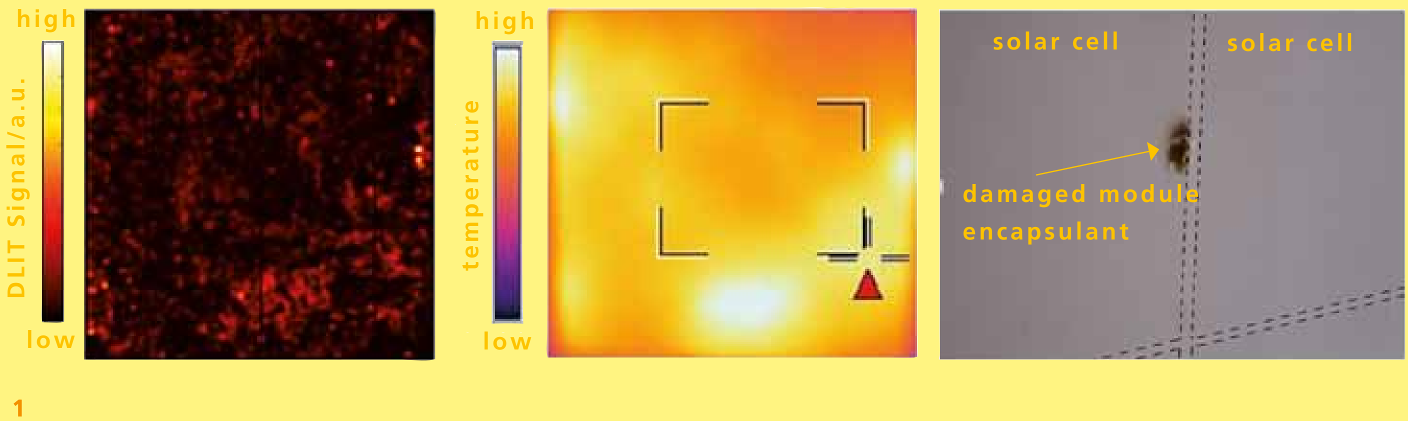
Time-dependent lifetime measurement methods based on luminescence, e.g. quasi-static luminescence, are practically unaffected by all of the artefacts mentioned above.

1 *The distribution of recombination losses in silicon can be determined qualitatively very quickly with the help of photoluminescence images. With our new QSSPL measurement unit (centre), we can calibrate a small area of a PL image (left) and thus quantify the spatially resolved distribution of charge carrier lifetime, a key parameter.*

At Fraunhofer ISE, quasi-static luminescence was therefore further developed into a method which can be applied broadly in silicon photovoltaics. The milestones to date in this development are:

- development of a dopant-independent method for lifetime determination
- lowering the lower limit for reliably measured charge carrier lifetimes to app. 1 µs (for usual doping concentrations)
- method for spatially resolved lifetime calibration by combination of static PL image (CCD) and quasi-static luminescence measurement
- extension of the palette of measurable samples to include solar cells and metallised wafers
- feasibility of injection-dependent lifetime measurement over an injection range from well below 10^{10} cm^{-3} up to radiation equivalent to ~50 suns
- development of independent measurement and analysis software

The work was supported by the Fraunhofer-Gesellschaft within the "Silicon BEACON" project.



DIODE BREAKDOWN IN MODULES OF MULTI-CRYSTALLINE SILICON SOLAR CELLS

Hot spots are one of the most common sources of damage to installed PV modules. One possible cause of hot spots is diode breakdown in solar cells of multi-crystalline (mc) silicon. Reservations concerning the effect of these breakdowns on module reliability represent one of the main obstacles to industrial application of the less expensive upgraded metallurgical grade (UMG) silicon. Investigations at Fraunhofer ISE demonstrated that a homogeneous distribution of breakdowns over the cell area does not lead to hot spots in the module, but can even have a beneficial effect on module properties.

Fabian Fertig, Stefan Rein, Ralf Preu

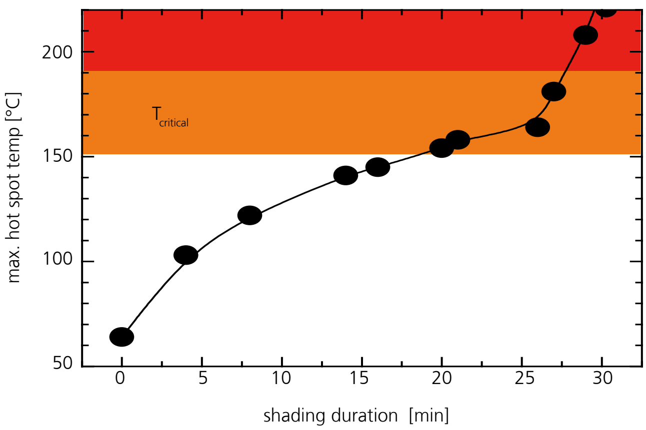
If sections of solar modules are shaded during operation (e.g. by foliage or snow), these sections consume power rather than generating it. This is because the voltage across a shaded cell is reversed by the other, illuminated cells in the module. If the solar cells contain local defects which lead to a local increase in current during reverse-bias operation, the local power dissipation within a module that is operated under partial shading conditions and the resulting temperature increase at these points can exceed critical limits. The result is irreversible damage to the module caused by a "hot spot" which is due to cell-specific properties (Fig. 1 and 2).

Investigations are being made at Fraunhofer ISE to determine which conditions cause diode breakdowns in solar cells of mc silicon to lead to hot spots. It has become evident that the heating process does not automatically lead to critical temperatures as long as the breakdowns are distributed homogeneously over the solar cell. A lower breakdown voltage, as in solar cells of UMG silicon, proves to be particularly advantageous, as in the worst case, the absolute value of dissipated power is lower than for solar cells with higher breakdown voltage. At the same time, a higher power yield is possible from shaded modules.

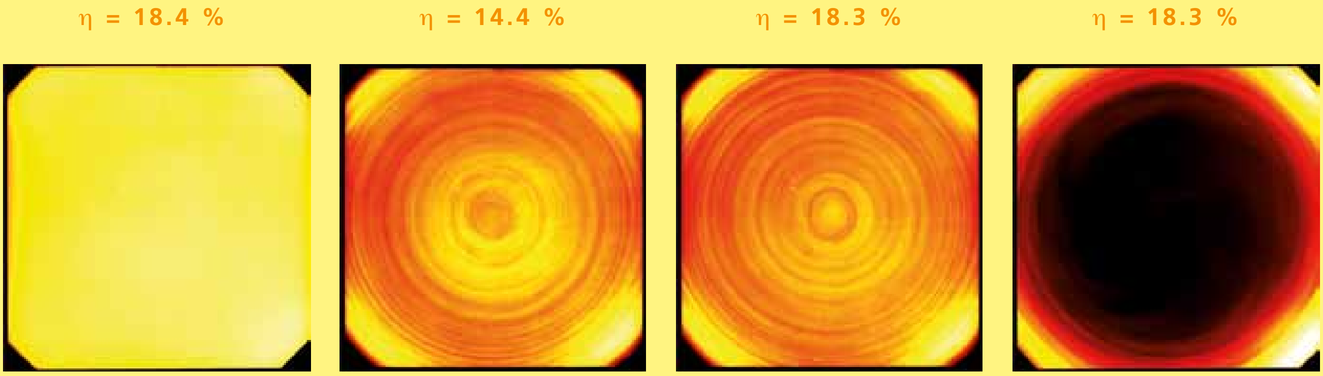
Parallel to the experimental investigations, the processes in the cell and the module are also modelled theoretically at Fraunhofer ISE and measurement methods are developed for in-line detection and analysis of defects in silicon solar cells.

This work was supported within an internal programme of the Fraunhofer-Gesellschaft.

1 *Dark thermography (DLIT) image of an mc-Si solar cell during operation under reverse bias before integration into the module (left), thermographic image of this solar cell when completely shaded in the module (centre) and photo of a module back sheet which has been damaged by a hot spot (right).*



2 *Change of the maximum hot spot temperature with time for a critical cell during continuous shading. The critical temperature, above which a module is irreversibly damaged, is usually in the range from 150 to 190 °C and depends on the module encapsulating material as well as external factors (e.g. wind speed).*



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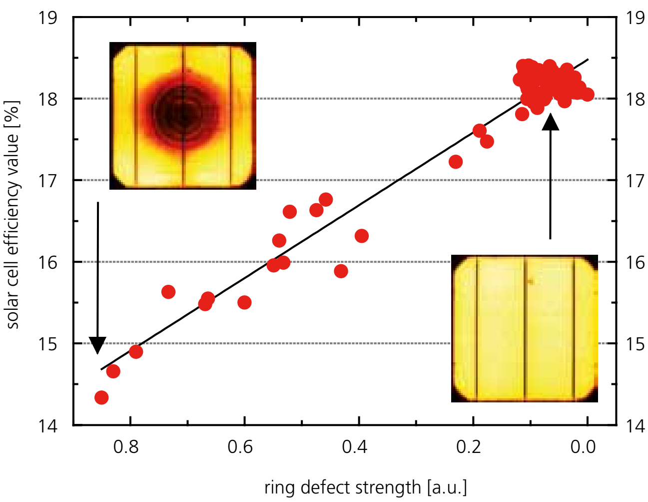
QUALITY CONTROL OF CZOCHRALSKI SILICON WAFERS

Quality control of silicon wafers as part of the incoming inspection for production is becoming increasingly important with respect to concepts for highly efficient solar cells. Within a materials study, photoluminescence (PL) of high-quality Czochralski (Cz) silicon wafers was used to detect material defects with strong recombination activity, which reduced the efficiency of solar cells from 18.5 % to 14.4 %. The new procedure is currently being further developed for application in the incoming inspection of wafers.

Juliane Broisch, Teodora Chipei, Jonas Haunschild, **Stefan Rein**, Isolde Reis, Ralf Preu

About half of all crystalline silicon solar cells are manufactured of monocrystalline Czochralski (Cz) silicon. Due to its high quality, this material is particularly interesting for novel, highly efficient solar cell concepts. Because these solar cell concepts have decreasing tolerance for fluctuations in the material quality, quality control is becoming increasingly important.



1 PL images of Cz silicon wafers in the as-cut stage with the efficiency values achieved by the finished solar cells. Wafers with different types of ring defects are shown, of which two are harmless and one strongly limits the efficiency value.

In order to gain information about the spectrum of defects which actually occur in Cz silicon and their effect on the solar cell performance, a broadly based materials study was carried out at Fraunhofer ISE, in which standard solar cells were produced from a large range of standard Cz silicon wafers supplied by various manufacturers. As can be seen in Fig. 2, the solar cell efficiency value varies over a very wide range from 14.4 to 18.5 %. The PL analysis of the solar cells shows that the low efficiency values are caused by ring-shaped defect structures, which display strong recombination activity and thus appear dark in the PL image. The so-called ring defect strength was determined from the PL images as a new material characteristic which correlates linearly with the efficiency value (Fig. 2).

As efficiency value losses of up to 4 % (absolute) are intolerable in industrial production, critical wafers must be identified and sorted out early in the process. This can already be done reliably by PL after emitter diffusion. As the series of images in Fig. 1 indicates, ring defects of differing strength can already be identified in the as-cut stage.

This work was supported within an internal programme of the Fraunhofer-Gesellschaft.

2 Solar cell efficiency as a function of the ring defect strength, which was determined by PL imaging of the finished solar cell. Two PL images are included as examples.

SURFACE CLEANING AND CHARACTERISATION

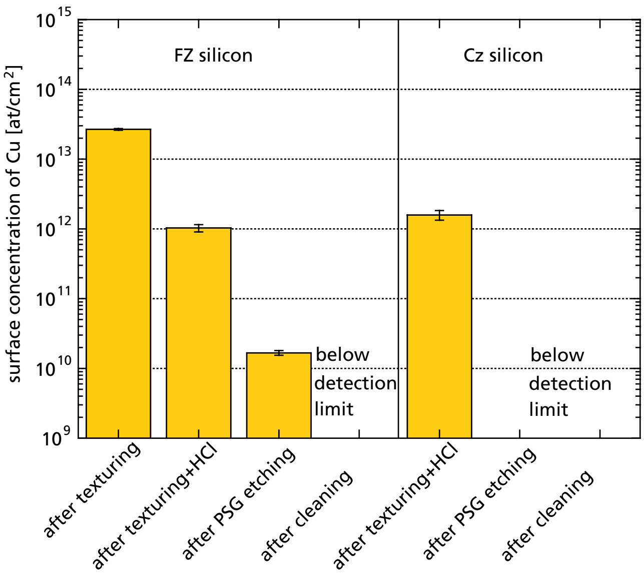
Surface cleaning plays a key role with regard to industrial implementation of concepts for highly efficient solar cells. In the development of suitable, cost-effective, wet-chemical cleaning sequences, suitable characterisation methods for the exact determination of metallic or organic residual contamination on the silicon surface must be available to evaluate the processes. Using these methods, cleaning sequences can be optimised regarding the application duration and dosage of chemicals and thus become more cost-effective, but the methods can also be applied as regular tests for quality control.

Katrin Birmann, Anamaria Moldovan, Antje Oltersdorf, **Jochen Rentsch**, Christian Sonner, Martin Zimmer, Ralf Preu

At Fraunhofer ISE, innovative cleaning processes for Si surfaces are developed which are adapted to the requirements of the photovoltaic industry. In particular, well-known sequences from the semiconductor industry, some of them very complex, should be simplified and expensive consumables such as hydrogen peroxide should be replaced. Initially, methods for trace analysis of metallic and organic impurities had to be developed so that the quality and effectiveness of the cleaning methods applied could be evaluated. In the so-called droplet surface etching (DSE) method, a droplet of fluid consisting of hydrofluoric acid and hydrogen peroxide collects the impurities which adhere to the surface. These droplets can subsequently be analysed by mass spectrometry, atomic absorption spectroscopy or optical emission spectroscopy. As a result, the surface concentration of the metallic impurities which are particularly critical for the solar cell (Cu, Fe, Ni, Cr etc.) can be detected with a detection limit of $1*10^9$ atoms/cm².

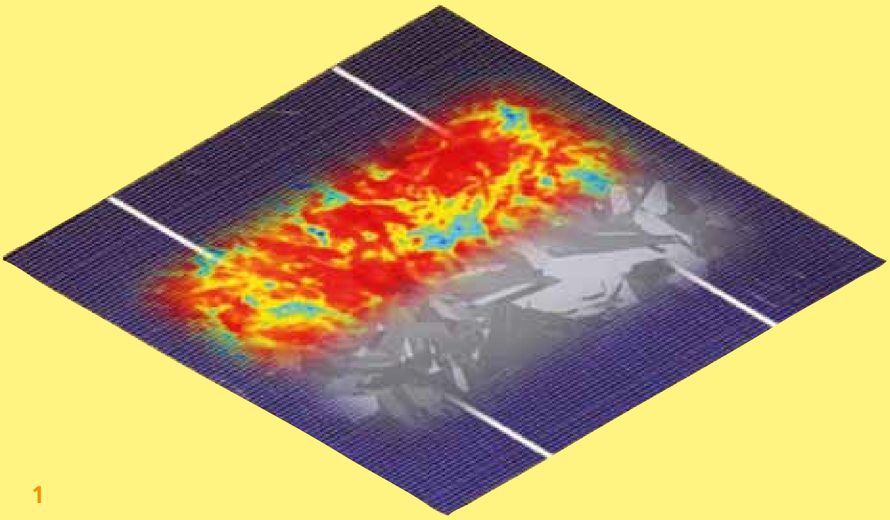
1 *Etching of the silicon layer near the surface with a fluid droplet consisting of hydrofluoric acid and hydrogen peroxide (Droplet Surface Etching).*

2 *Equipment for optical emission spectroscopy and atomic absorption spectroscopy to determine metallic impurities in wet chemical solutions.*



3 *Surface contamination of float zone (FZ) and Czochralski (Cz) silicon wafers with copper (Cu), detected with ICP mass spectroscopy after various cleaning process steps following alkaline texturing (HCl: hydrochloric acid bath, PSG: phosphorus silicate glass).*

The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and our project partners, Stangl Semiconductor AG, Heraeus Noblelight GmbH, Roth&Rau AG, Astex GmbH and LayTec GmbH.



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PREDICTION OF SOLAR CELL PARAMETERS FROM LIFETIME MEASUREMENTS

For multicrystalline silicon, the central question concerning material characterisation is the influence of electrical material quality on the solar cell efficiency. Usually, the charge carrier lifetimes, e.g. of electrons for boron-doped material, are measured to characterise the electrical material quality. We have measured the lifetime for different charge carrier densities and combined this with a simulation. This allows us to predict the cell efficiency value quantitatively and furthermore to make a detailed analysis of the material-related losses for all solar cell parameters.

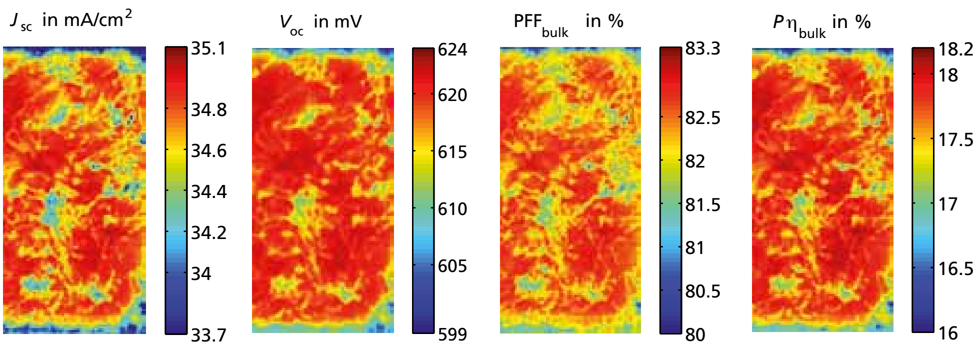
Johannes Giesecke, Martin Hermle, **Bernhard Michl**, Marc Rüdiger, Martin Schubert, Wilhelm Warta, Stefan Glunz

The photoluminescence imaging (PLI) method was further developed to allow reliable values for cell parameters to be determined from lifetime measurements even for regions characterised by short lifetimes. The material quality is determined with the spatially resolved and injection-dependent procedure for a wafer after the relevant high-temperature steps and with appropriate surface passivation, providing direct access to the material information that is relevant for the cell efficiency. It is thus feasible to take into account the fact that the charge carrier density in the solar cell also

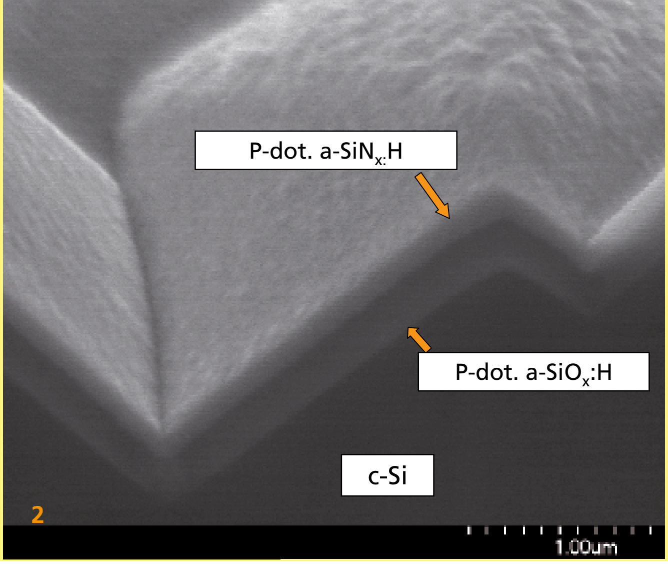
1 Solar cell, silicon material and an image of the solar cell efficiency (collage).

depends decisively on the operating state (operation from short circuit to open circuit) and on the cell concept. With the aid of a simulation, it is now possible to calculate the local cell parameters for every pixel of the PLI measurement (Fig. 2). It becomes evident that the local cell efficiency in regions with high defect density is lowered by up to 2 $\%_{abs}$. The electrical quality has the greatest influence on the short circuit current. This is due to the significantly reduced charge carrier lifetime in short circuit operation as compared to open circuit operation. In addition, the fill factor is found to be lowered by the material quality. This result is a direct consequence of the lifetime varying with the injection level. With the help of a special averaging procedure, global solar cell parameters can also be calculated. These global values agree very well with the values measured for processed solar cells and allow detailed, material-dependent loss analysis at cell level.

The project was supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and within the "ALBA II" project.



2 Spatially resolved analysis of the short circuit current density J_{sc}, the open circuit voltage V_{oc}, the fill factor PFF_{bulk} and the resulting cell efficiency η_{bulk}. All images have been scaled in the same way. The maximum is the value which could be obtained without material-related losses. The minimum for the J_{sc}, V_{oc} and PFF_{bulk} images represents a loss of 4 %; the minimum for the η_{bulk} image represents a loss of 12 %.



FUNCTIONAL PECVD MULTI-LAYER STACKS

PECVD multi-layer stacks as anti-reflective coatings and for surface passivation represent the state of the art for crystalline silicon solar cells. With a view to further cost-saving potential, multi-functional PECVD multi-layer stacks were developed at Fraunhofer ISE which can fulfil several tasks simultaneously. For instance, they serve not only to passivate the surface but also as a dopant source or as a diffusion barrier. With the help of these multi-layer stacks, complex processing sequences could be significantly simplified in future.

Marc Hofmann, Jan Jeurink, Bishal Kafle, Roman Keding, Norbert Kohn, Saskia Kühnhold*, Florian Pillath, **Jochen Rentsch**, Pierre Saint-Cast, Johannes Seiffe*, Daniel Trogus, Dirk Wagenmann, Ralf Preu

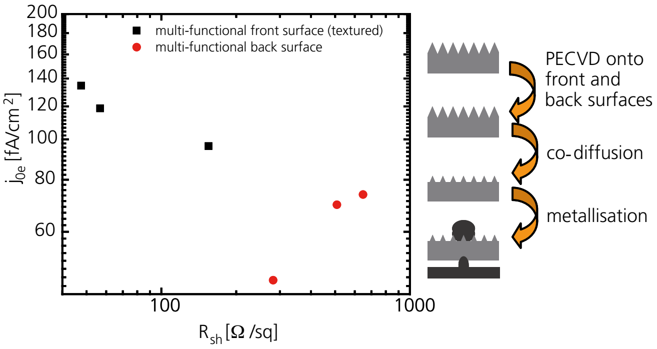
*Freiburger Materialforschungszentrum FMF, Albert-Ludwigs-Universität Freiburg

With the help of PECVD-deposited, doped silicon dioxide layers, it was already demonstrated in the past that very homogeneous emitters can also be produced on strongly textured surfaces. In more recent investigations at Fraunhofer ISE, a passivation layer (e.g. of SiN_x or AlO_x) was additionally deposited onto the doped layer. This type of multi-functional, multi-layer stack thus serves both for single-surface emitter formation and surface passivation. It was observed that the high-temperature step also reduced the porosity of the passivation layer, which brought advantages for a later galvanisation step to produce contacts. By sequential coating of the front and back surfaces of a solar cell with oppositely doped passivation and doping layers and subsequent co-diffusion, emitter saturation current densities below 100 fA/cm² were achieved for the front-surface emitter and below 20 fA/cm² for a boron-doped back-surface field on p-doped, textured substrates. Future processing sequences to produce solar cell structures that are passivated on both sides and locally contacted could thus be simplified significantly.

The work is supported by the German Federal Ministry of Education and Research (BMBF).

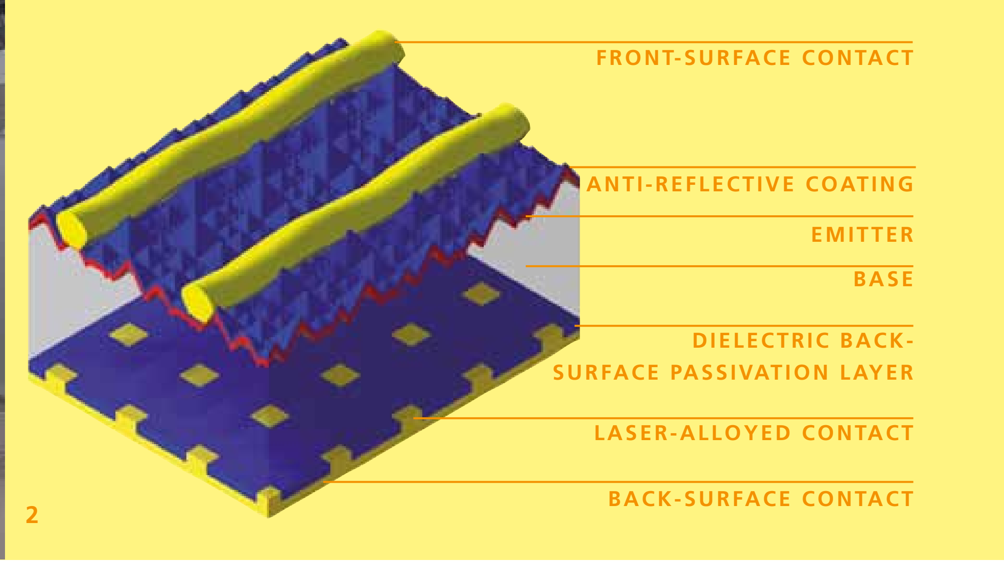
1 *Microwave linear plasma excitation of a PECVD in-line facility to deposit the doped passivation and dopant layers. The homogeneous plasma region is about 1 m wide, allowing carriers with up to 5 x 5 wafers with an edge length of 156 mm to be processed in parallel.*

2 *Doped a-SiN_x:H and a-SiO_x:H layers that were deposited by PECVD processes onto an alkaline textured pyramidal surface.*



3 *Resulting emitter saturation current density j_{0e} and emitter sheet resistance R_{sh} after co-diffusion of doped PECVD multi-layer stacks for the back and front surfaces of the solar cell.*

1



2

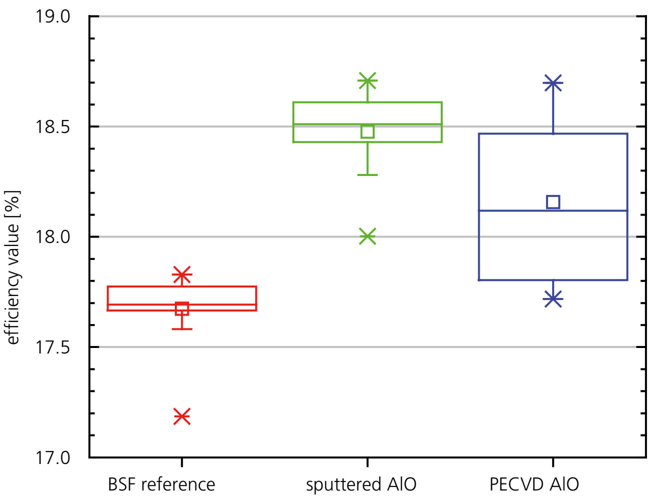
SPUTTERED ALUMINIUM OXIDE FOR PASSIVATION OF SOLAR CELLS

Good passivation of solar cell surfaces is essential to achieve higher efficiency values and is thus of great interest to the industry. Aluminium oxide coatings are excellently suited for p-doped silicon wafers and for p-type emitters. Sputtering technology is a method to deposit aluminium oxide coatings which offers potential to reduce the costs of this production step. High efficiency values exceeding 18.7 % were achieved with this method.

Georg Krugel, Winfried Wolke, Ralf Preu

1 *ATON500 sputtering facility from Applied Materials at Fraunhofer ISE.*

2 *Schematic diagram of a back-surface passivated solar cell with laser-alloyed contacts. An additional passivation layer (blue) of aluminium oxide with a coating of silicon nitride is located between the metallisation layer over the entire back surface (yellow) and the base to reduce the number of recombination processes and thus make higher efficiency values feasible.*



3 *The efficiency value of the p-type solar cells with a sputtered back-surface passivation layer of aluminium oxide is higher than that of the back-surface field (BSF) reference cells with a contact over the entire back surface and even than that of solar cells with PECVD aluminium oxide.*

Solar cells with passivated back surfaces represent an established concept to achieve high efficiency. Deposition of the coating for back-surface passivation is an important step in the process, which still offers potential for cost reduction and for which higher turnover would be desirable.

Sputtering technology to deposit aluminium oxide (Fig. 1) was developed at Fraunhofer ISE as a promising alternative to the ALD (Atomic Layer Deposition) and PECVD (Plasma Enhanced Chemical Vapour Deposition) methods that have been used to date. It avoids the need to use readily flammable and expensive trimethyl aluminium.

Back-surface passivated solar cells with laser-alloyed contacts were produced by applying sputtering technology to deposit the coating (Fig. 2). Efficiency values exceeding 18.7 % were achieved (Fig. 3). It is expected that optimisation of the process parameters will result in further improvement in the cell parameters.

IN-LINE ANNEALING – HIGH THROUGHPUT AND CONTROLLED ATMOSPHERE

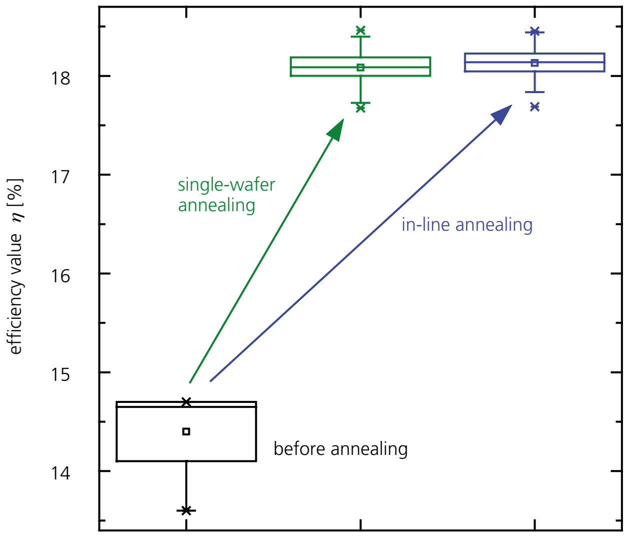
Most high-efficiency concepts for silicon solar cells feature dielectrically passivated surfaces and/or novel metallisation approaches. For these structures, thermal treatment at the end of the cell processing is useful or even essential to achieve high efficiency. Up to now, usually quartz tube furnaces with a small volume have been used for the annealing processes. However, these do not offer the throughput needed for industrial applications and in addition, automation is complicated. An in-line process has been developed at Fraunhofer ISE which enables annealing processes to be carried out with a high throughput under a controlled atmosphere, thus meeting the specifications for industrial processes

Daniel Biro, **Sebastian Mack**, Daniel Scheffler, Andreas Wolf, Ralf Preu

Concepts for highly efficient solar cells with dielectrically passivated surfaces are currently being transferred to production. Many of these passivation layers require thermal treatment to activate the surface passivation. Similarly, alternative metallisation procedures, e.g. two-stage metallisation, require an annealing process to improve adhesion and to reduce the contact resistance between the metal and silicon.

In co-operation with Centrotherm, a manufacturer of processing equipment, a prototype facility for in-line annealing (Fig. 1) was installed at Fraunhofer ISE. This demonstrated annealing for a high-throughput, in-line process for the first time. The in-line process avoids time-consuming flushing and loading steps, which has a positive effect on the throughput and the processing costs. The existing facility allows a throughput of app. 700 wafers/h for a plateau duration of 2 minutes. A larger system (five tracks, longer plateau zone) would enable an increase to more than 3000 wafers/h. Gas locks at the inlet and outlet of the furnace effectively

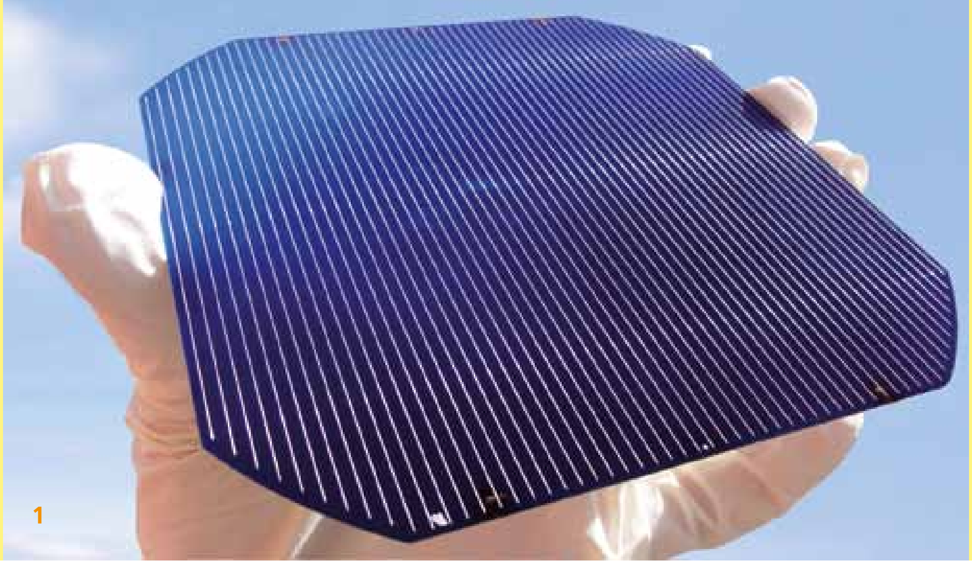
1 Prototype of the in-line furnace to anneal crystalline silicon solar cells with an edge length of 125 mm or 156 mm. The furnace has two processing tracks (left: complete facility; right: detail)



2 Distribution of efficiency values for monocrystalline silicon solar cells with passivated rear surfaces, measured before and after an annealing process in inert forming gas. The results of the in-line process are similar to those from single-wafer processing.

isolate the processing atmosphere from the laboratory. By using inert forming gas, an oxygen concentration of less than 1 ppm can be achieved in the processing chamber. To evaluate the prototype system, processes were implemented under identical conditions in the in-line furnace and in a single-wafer reactor as a reference system. The annealing process causes a significant increase in the efficiency value of solar cells with dielectrically passivated rear surfaces (Fig. 2). The in-line process achieves the same level as the reference system.

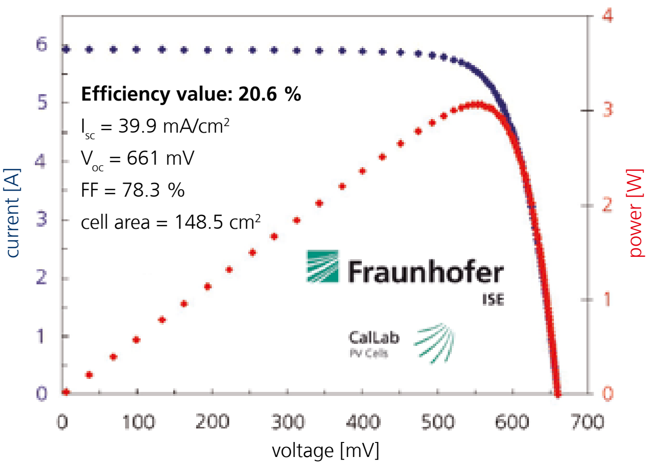
The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).



PASSIVATED MWT SOLAR CELLS WITH DISPENSED FRONT CONTACTS

Passivated metal wrap-through (MWT) solar cells combine the advantages of back contact cells with those of surface passivation in a single solar cell. The additional effort to produce these solar cells has been reduced to a single step: laser drilling of the vias. Applying manufacturing processes based on industrial production technology, efficiency values of up to 20.2 % were achieved with screen-printed metallisation and record efficiency values of up to 20.6 % were reached with dispensed front-surface metallisation on large-area monocrystalline p-type silicon wafers (float zone, 125 x 125 mm²).

Daniel Biro, Florian Clement, Harald Gentischer, Ulrich Jäger, **Elmar Lohmüller**, Sebastian Mack, Maximilian Pospischil, Jan Specht, Alma Spribille, Benjamin Thaidigsmann, Andreas Wolf, Ralf Preu

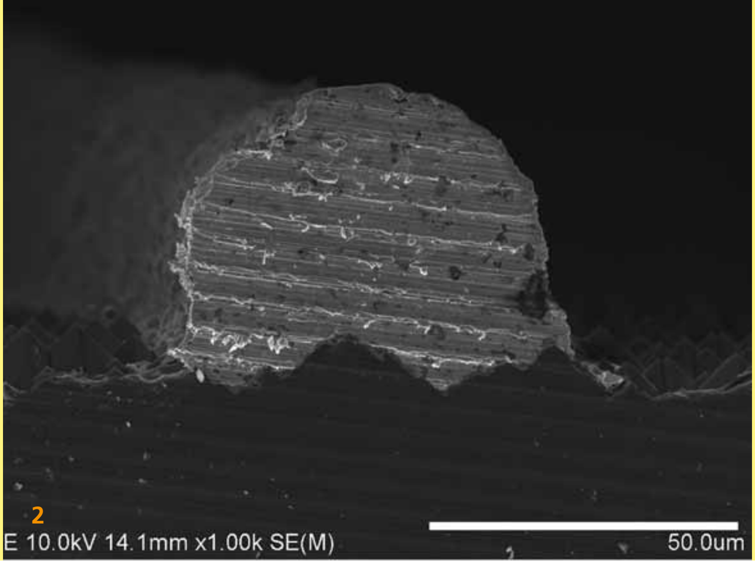


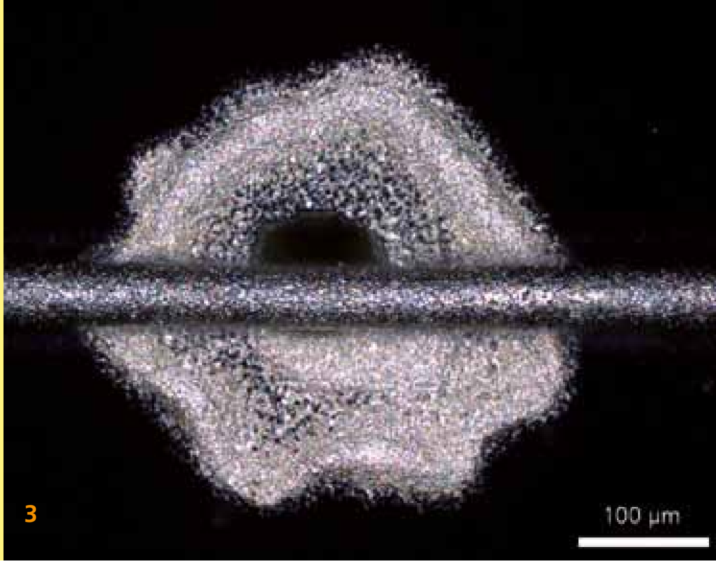
4 *Current and power versus voltage for a passivated p-type MWT solar cell with dispensed front contacts and a record efficiency value of 20.6 % (confirmed by Fraunhofer ISE CalLab PV Cells). Efficiency value: 20.6 %*

1 *Front surface of a monocrystalline passivated MWT solar cell with screen-printed metallisation. Three rows of wrap-through vias conduct the current collected on the front surface to the external electric contacts mounted on the back surface.*

Conventional silicon solar cells with aluminium contacts covering the entire back surface represent the most common type of solar cell in the PV industry today. Nevertheless, the efficiency of these solar cells is limited, primarily due to the large optical and electrical losses on the back surface and significant shading of the front surface due to the contact grid with bus bars.

To achieve the highest efficiency values in the industrial context, we developed various solar cell concepts in our Photovoltaic Technology Evaluation Centre (PV-TEC), including the HIP-MWT (High-Performance Metal Wrap-Through) concept: To reduce shading of the front surface by up to 50 $\%_{rel}$, the bus bars for external contacting were relocated from the front to the back surface and connected electrically by laser-drilled vias with the front contact grid (Fig. 1 and 5). In addition, the solar cell surfaces are passivated to minimise optical and electrical losses, which leads to a significant reduction in recombination losses (PERC concept: passivated emitter and rear cell). In contrast to MWT-PERC solar cells, which are similar but more complicated to produce, we were able to save on processing steps for structuring the emitter on the back surface of the solar cell with our newly developed HIP-MWT solar cells (Fig. 5). Compared to the reference process to produce passivated PERC solar cells with conventional front contacts, the laser-drilling of holes to connect the front contact to the back is the only additional step needed.



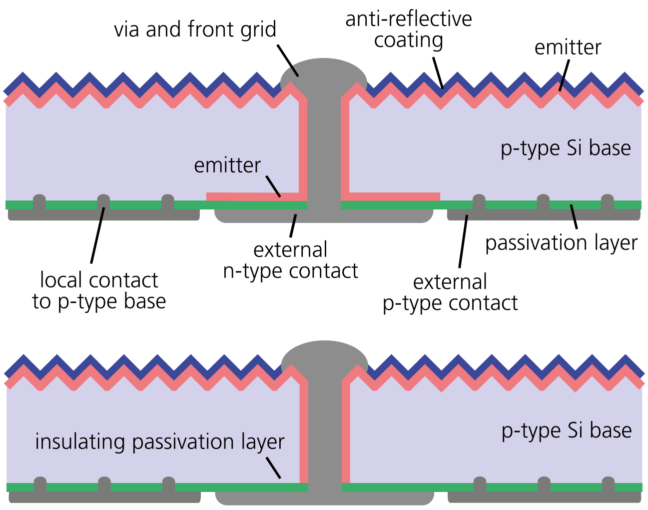


2 *Scanning electron micrograph of a dispensed front contact. The aspect ratio (ratio of height to width) is significantly increased with respect to a screen-printed contact.*

3 *Optical microscope image of a dispensed front contact near a via. The via metallisation is also visible.*

Furthermore, we applied novel metallisation technology (dispensing, Fig. 2 and 3) for the front surface of the solar cell to produce a large-area p-type silicon solar cell of cost-effective Cz silicon with an efficiency value exceeding 20 %. This represents a very important milestone marking progress in technological development at Fraunhofer ISE. The significant increase in efficiency is mainly due to a reduction in the contact finger width on the front surface by up to 50 % compared to screen-printed metallisation. Solar cells based on high-quality p-type FZ silicon with the same configuration and parallel processing achieved a record efficiency value of 20.6 % over a large cell area with an edge length of 125 mm (Fig. 4).

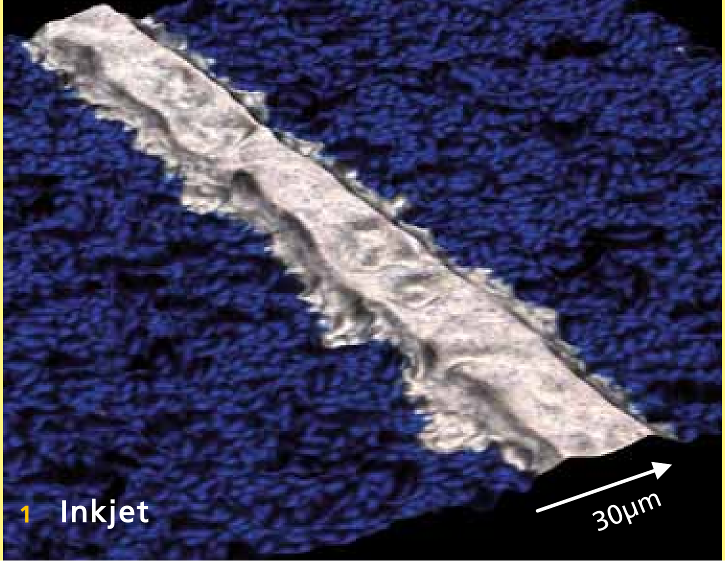
Further increases in efficiency are anticipated as a result of optimised processes and solar cell structures arising from work currently in progress. The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU), the European Commission and industrial partners.



5 *Schematic cross-sections of passivated MWT solar cells: conventional MWT-PERC concept (above), simplified HIP-MWT concept (below). The HIP-MWT solar cell does not have any back-surface emitter zone.*

Metallisation	Material	Efficiency Value (%)
Screen-printing	Cz-Si	19.6
	FZ-Si	20.2
Dispenser	Cz-Si	20.1
	FZ-Si	20.6

6 *Efficiency values achieved to date for passivated MWT solar cells. The edge length of the monocrystalline p-type Si wafer is 125 mm, the values for Cz-Si relate to measurements after deactivation of boron-oxygen complexes in the bulk silicon.*



FINE LINE PRINTING AND DEVELOPMENT OF METAL PASTES

The primary goal of solar cell development is to reduce the levelised cost of photovoltaic electricity generation by improving efficiency and lowering the processing and material costs. One promising approach to reach this goal is optimisation of the metallic contacts on the front surface of the cell. We succeeded in producing narrower, better conducting solar cell contacts by applying novel printing techniques (inkjet and aerosol jet) to produce seed layers that were then reinforced by galvanisation.

1 *Inkjet-printed seed-layer contact.*

2 *Three-roll mill to homogenise and disperse pastes.*

Sebastian Binder, Aleksander Filipovic, Markus Glatthaar, **André Kalio**, Katja Krüger, Johannes Spannagel, Daniel Schmidt, Stefan Glunz

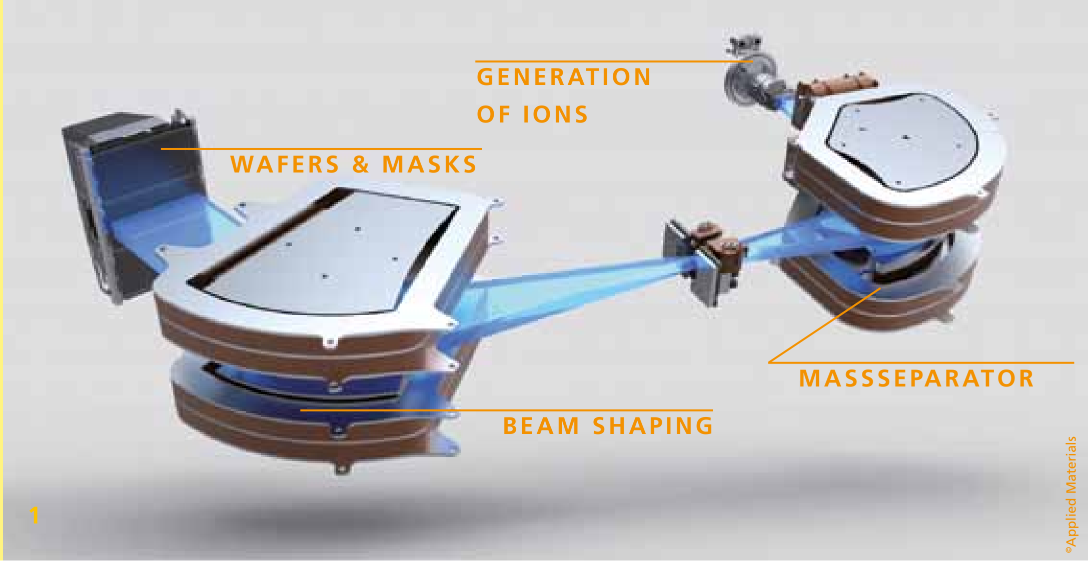
The front surface of a solar cell is usually metallised by screen-printing with silver-based pastes. Finger widths of app. 100 µm are achieved with this procedure, which leads to a relatively high consumption of silver and appreciable shading of the solar cell surface.

To optimise the front metallisation, we are developing new printing techniques which feature narrow line widths of about 35 µm and very low contact resistance between the metal and the semiconductor. After the ink has been sintered, the lines are galvanised with a sequence of nickel, copper and tin. This results in contacts with very high conductivity, low material costs and good long-term stability.

We apply high-resolution printing techniques such as aerosol jet and inkjet printing. In aerosol printing, a metal-containing ink is atomised to form an aerosol and is focussed onto the solar cells by a jet with an enveloping gas sleeve. A demonstrator of this technology with a high throughput is currently being developed. In inkjet printing, droplets of ink are deposited onto the wafer from an array of jets, each with a diameter of about 25 µm. Either a seed layer or a complete contact finger can subsequently be formed of these droplets.

As the ink and the printing technique used are mutually dependent, we also develop inks and pastes for metallising boron and phosphorous emitters. We are able not only to produce the components ourselves, e.g. glass for the pastes, but also to completely prepare the pastes and inks. One requirement for highly efficient solar cells is the ability to contact emitters with a low dopant concentration. At present, we can use the inks we have developed to contact emitters with a surface concentration down to $N_D = 8 \cdot 10^{18}$ cm^{-3}, which offers potential for very high efficiency.

The project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).



HIGHLY EFFICIENT SILICON SOLAR CELLS WITH ION IMPLANTATION

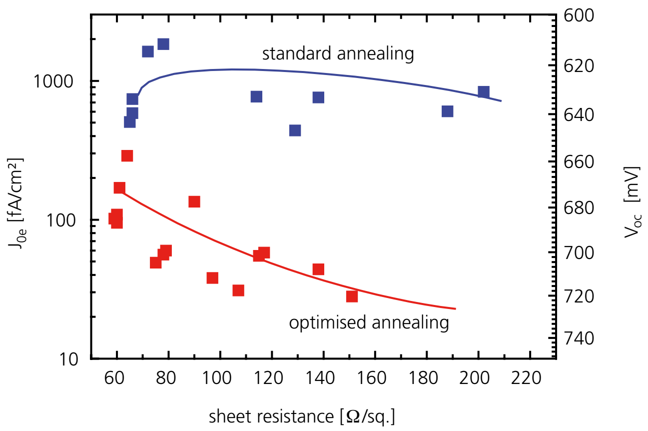
Ion implantation is the standard technology to achieve local doping in microelectronics. As many concepts for highly efficient solar cells require local doping, ion implantation is also very interesting as processing technology for photovoltaics. In co-operation with VSEA, a manufacturer of ion implanters, we have succeeded in producing a completely implanted rear-contact (RC) solar cell for the first time, with an efficiency value of 20 %. By optimising the thermal annealing step which is needed for implanted cells, we were able to achieve an efficiency value of 21.7 % for a cell structure with contacts on both surfaces, which represents a global record for an implanted solar cell.

Nicholas Bateman*, **Jan Benick, Martin Hermle**,
Nikolas König, Antonio Leimenstoll, Christian Reichel,
Sonja Seitz, Felix Schätzle, Stefan Glunz

*Varian Semiconductor Equipment Associates

Local doping profiles are an important pre-requisite for many concepts for highly efficient solar cells. Usually several processing steps are needed when diffusion in classic tubular furnaces is applied, e.g. the deposition and structuring of a diffusion barrier. By contrast, templates can be used in ion implantation, so that local doping profiles can be created in a single processing step. This reduces the number of processing steps appreciably, particularly for more complex structures, e.g. back-surface contacted solar cells. In co-operation with the Varian company, we have succeeded in producing the first completely implanted RC solar cell with an efficiency value of 20 %.

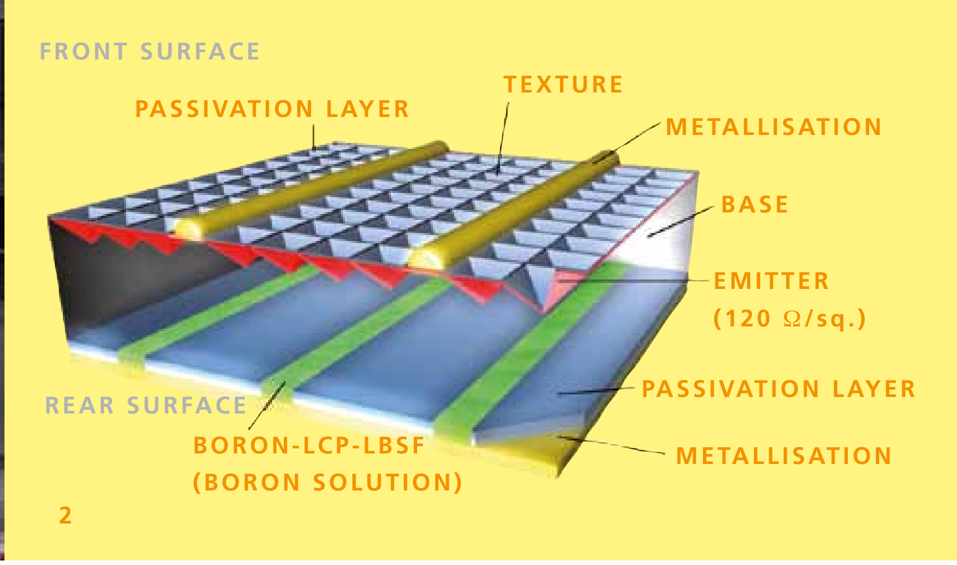
1 *Principle of local doping with ion implantation.*



2 *Effect of the annealing process on the quality of the implanted boron emitter (lines are purely guides to the eye).*

As the crystal structure is damaged during implantation by the ion beam, it must be annealed in a subsequent high-temperature step. We are developing optimised processes and processing sequences for this step, which allow the surface to be passivated simultaneously with the annealing. By applying these optimised processes, we were able to produce boron and phosphorus doped emitters with very low dark saturation currents (Fig. 2). The best n-type solar cells with an implanted boron emitter (produced with optimised annealing processes) achieved an efficiency value of 21.7 % – a global record for an implanted solar cell.

1

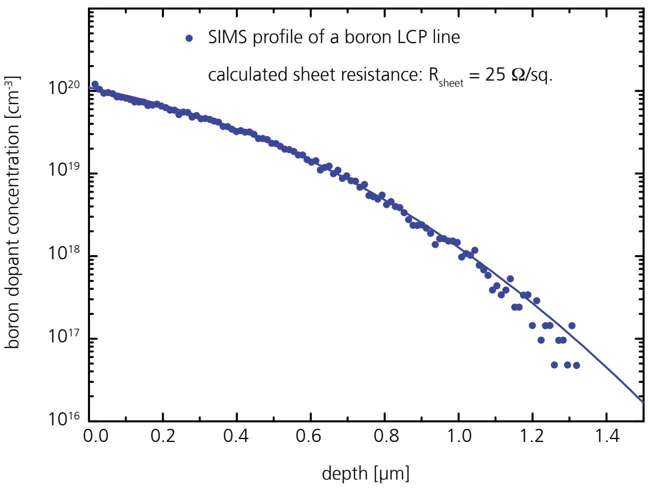


2

LOCAL BORON DOPING FOR HIGHLY EFFICIENT SILICON SOLAR CELLS

Despite successful process optimisation, the efficiency of industrially produced solar cells is presently limited by effects relating to the cell design, including the metal contact over the entire back surface of the cell. In order to overcome these limits, an essential step is to introduce a passivated back surface which possesses only locally, strongly doped contacts. Laser chemical processing (LCP) is a procedure in which a liquid-guided laser beam is used to open passivation layers locally and simultaneously apply local boron or phosphorus doping, depending on the choice of liquid.

Christoph Fleischmann, Markus Glatthaar, Sybille Hopman, **Sven Kluska**, Martin Lieder, Matthias Mesec, Stefan Glunz



3 *Measured boron dopant concentration of a line structure doped with boron LCP.*

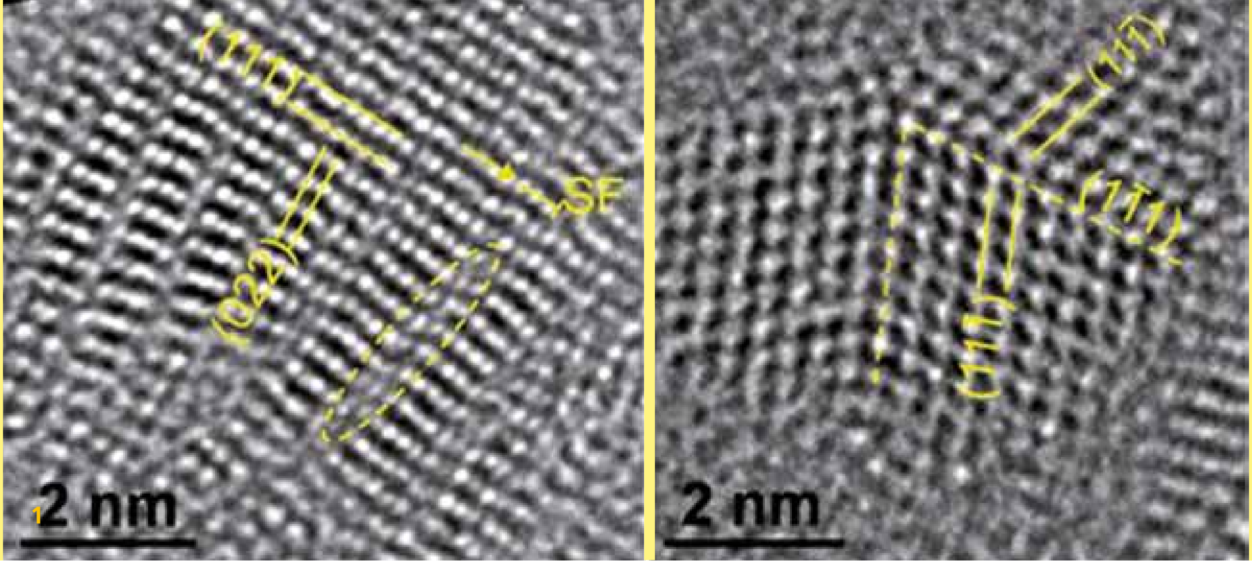
1 *LCP processing of a silicon wafer.*

2 *Schematic drawing of a highly efficient solar cell with a back-surface boron LCP-LBSF.*

If a liquid containing boron is used as the beam guide for the laser process, this presents a simple method to structure passivation layers locally and simultaneously to dope locally with boron in the holes, as is required e.g. for a "local back surface field" (LBSF) in concepts for highly efficient solar cells. This method ensures that the opening and the local doping are automatically perfectly aligned with each other. In comparison to contacts which are locally doped with aluminium, boron-doped contacts feature appreciably lower recombination relative to the contact area.

In the context of work on local boron doping with LCP, the integration of the boron LCP doping process into a manufacturing process for highly efficient silicon solar cells was demonstrated experimentally. The passivated back surface was locally opened and doped with the aid of boron LCP. An alkaline boron solution was used as the liquid, which made a surface doping concentration of $N_{A,boron} > 10^{20}$ cm^{-3} (Fig. 3) feasible due to its high boron content.

The solar cells with boron LCP displayed a clear advantage compared to cells with undoped LCP openings processed with water as the beam-guiding fluid and achieved efficiency values of up to 20.9 %.



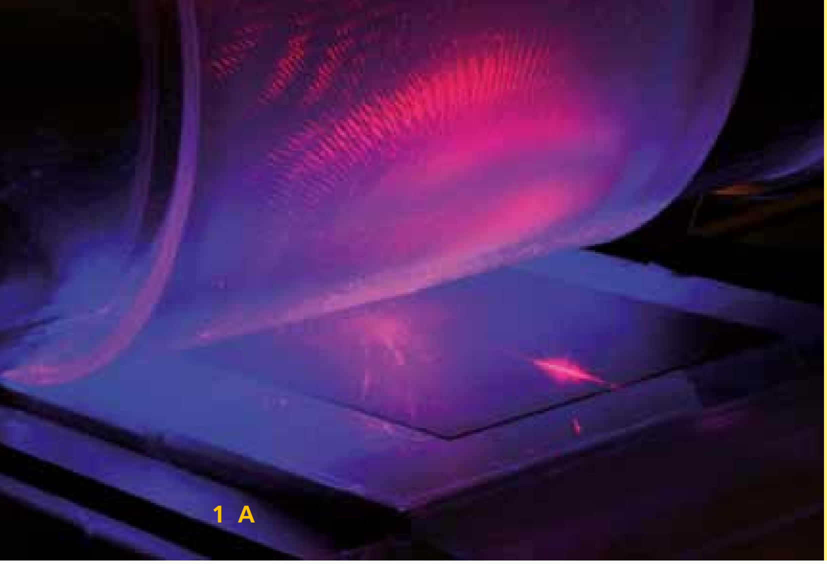
TANDEM SOLAR CELLS BASED ON CRYSTALLINE SILICON

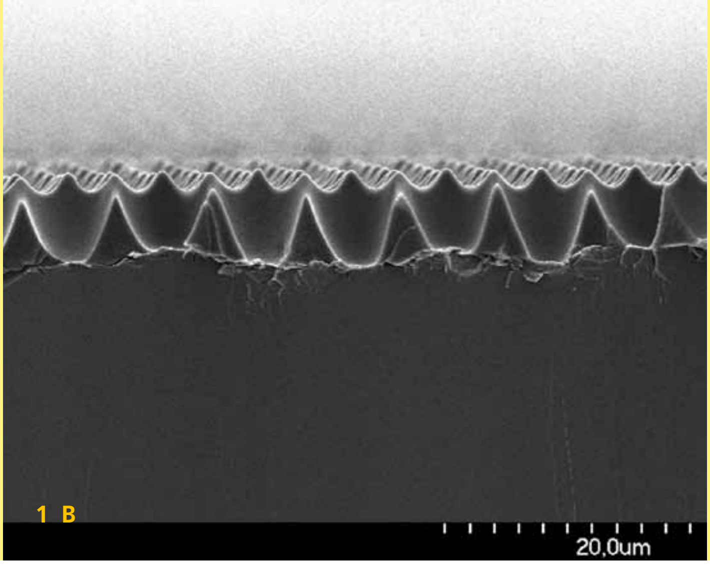
Tandem solar cells based on crystalline silicon represent a promising approach to break through the conversion limits of conventional single solar cells. The solar spectrum can be converted much more efficiently by tandem solar cells, in which one or more solar cells with a larger energy gap than that of crystalline silicon are stacked on top of the silicon solar cell. The currently dominant solar cell technology based on silicon wafers could be revolutionised. At Fraunhofer ISE we combine established technology with new and innovative materials. One possibility here is an absorber material of Si nanocrystals, which are integrated into a transparent matrix and absorb light very effectively and selectively. The energy gap of such a material is determined by the dimensions of the nanocrystals.

Martin Hermle, **Stefan Janz**, Philipp Löper, Stefan Reber, Manuel Schnabel, Anke Witzky, Stefan Glunz

1 *High-resolution transmission electron micrograph (HRTEM) of $Si_{1-x}C_x$ / SiC multi-layers after annealing at 1000 °C. The left-hand image shows a silicon carbide nanocrystal and the right-hand image presents a silicon nanocrystal, together with the indices for grid planes. The images were prepared in co-operation with the University of Tübingen and the Forschungszentrum Jülich.*

Tandem solar cells of crystalline silicon allow the efficiency to be increased in comparison to conventional silicon solar cells. The particular attraction of this type of tandem solar cell is that it would further develop a commercially successful and dominating technology. At Fraunhofer ISE, we are applying our comprehensive knowledge of silicon carbide (SiC) and using this as the matrix material for Si nanocrystals (Fig. 1). In addition to preparing these Si nanomaterials by plasma-enhanced chemical vapour deposition (PECVD) and solid-phase crystallisation (SPC) or from solution, we are concentrating on the crystallographic and electrical characterisation of the structures and the development of simple test structures. One important question here concerns the influence of dopants and their behaviour during the various high-temperature steps. Furthermore, we apply electro-optical measurement methods like time-resolved photoluminescence and specially developed measurement structures to determine the transport and recombination properties of the nanomaterials. Important conclusions can be drawn on the dominant physical transport mechanisms in the directions parallel and perpendicular to the multi-layer structure from electrical conductivity measurements at different temperatures and under irradiation with different optical spectra. For the monolithic integration of these new absorber materials into a tandem solar cell, we are developing novel tunnel contacts as well as the necessary solar cell processes, both for crystalline silicon thin-film solar cells and for wafer-based solar cells.





PHOTON MANAGEMENT STRUCTURES FOR SILICON SOLAR CELLS

The development of silicon solar cells is characterised by two important trends: To save material, the wafer thickness has been continually reduced. Despite the smaller amount of absorber material, increasingly higher external quantum efficiency values are a goal. These two opposing lines of development can be united only if photonic structures are applied for light trapping. At Fraunhofer ISE, we are therefore developing different concepts for microstructured and nanostructured surfaces which exploit both geometric-optical and diffractive effects for photon management. In addition to theoretical understanding and optimised designs for these structures, a central objective is the large-area production of the identified structures.

Jan Benick, **Benedikt Bläsi**, Johannes Eisenlohr, Jan Christoph Goldschmidt, Hubert Hauser, Martin Hermle, Stefan Janz, Alexander Mellor*, Bernhard Michl, Sonja Seitz, Christian Walk, Christine Wellens, Stefan Glunz

* Instituto de Energía Solar, Universidad Politécnica de Madrid

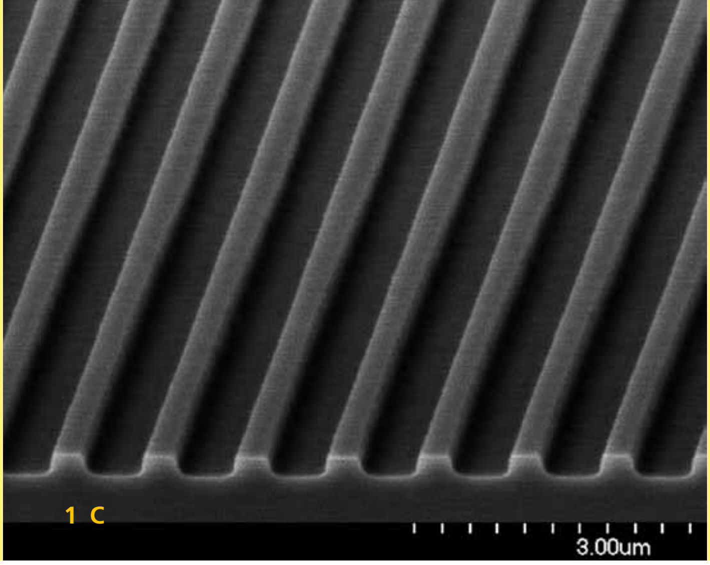
1 *(A) Newly developed unit for roller NIL, in which etching masks can be prepared with extremely fine structures. Red laser radiation demonstrates the light-deflecting effect of the honeycomb texture. (B) Etching mask structured by roller NIL on a rough mc-Si substrate. (C) A linear grating etched into silicon by NIL. (D) Monolayer of SiO_2 spheres with a diameter of 350 nm on a silicon wafer.*

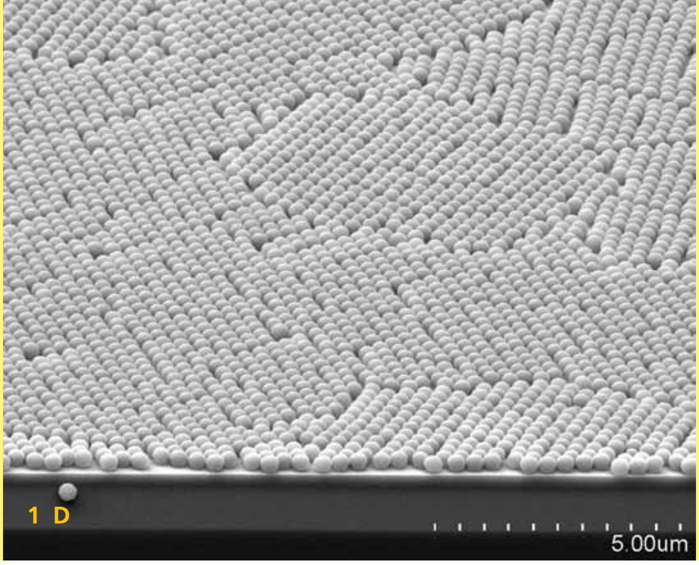
Honeycomb textures for the front surface of cells

Front-surface textures which are commonly applied industrially to multi-crystalline silicon solar cells do not result in optimal trapping of the incident radiation. The so-called honeycomb texture is significantly more efficient, which was already used by Fraunhofer ISE in 2004 to achieve the world record for this type of material. To enable this texture to be produced industrially, we are working on processes which are intended to replace the photolithography which is commonly used on a laboratory scale for highest-efficiency solar cells. A replication technique is used, nano-imprint lithography (NIL), in which the etching mask needed for well-defined structures is prepared in an embossing process. A specially developed roller NIL unit allows etching masks to be structured with very high resolution in a continuous in-line process, so that this process can be integrated into production lines (Fig. 1A). The master structures of the hexagonal pattern which are needed for die production can be created over large areas with interference lithography. Up to now, we have combined NIL with plasma-etching processes to obtain very effective front-surface textures (Fig. 1B and 2). In future, we will also investigate the combination of NIL with wet chemical etching processes.

Rear-surface gratings based on interference lithography

A further concept for photon management is based on diffractive gratings on the rear surface of the solar cell. In particular, they deflect long-wavelength radiation, which is only weakly absorbed, onto long pathways through the cell by diffractive effects. In this way, this spectral region can be converted more efficiently. We also apply NIL here to transfer





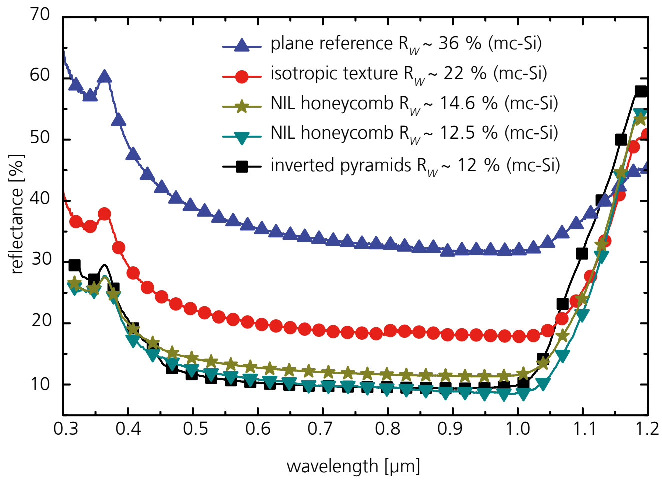
minute structures onto large wafer areas on the basis of master structures that are prepared by interference lithography. These photonic structures can subsequently be transferred via plasma-etching processes onto the silicon substrate. With this method, we have implemented linear and crossed gratings as well as hexagonal structures with periods of 1 µm, and have characterised their effect to increase absorption (Fig. 1C and 3).

Rear-surface structures with nanospheres

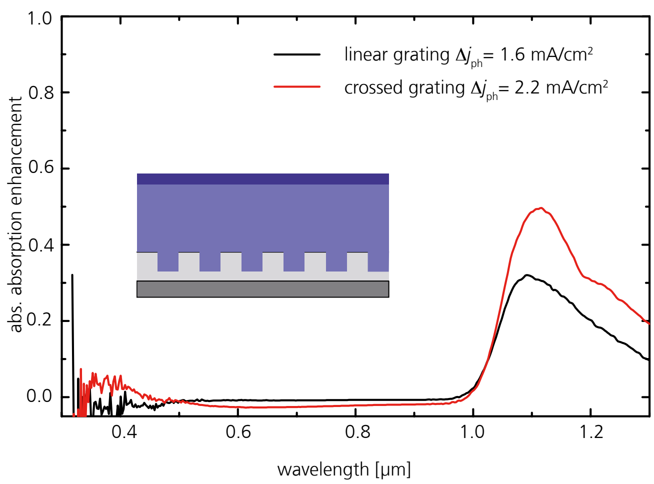
Another possibility to create diffractive rear-surface structures is by application of hexagonally packed SiO_2 nanospheres (Fig. 1D) which are embedded in a matrix of high refractive index. The advantage of this approach is that the surface of the silicon wafer is not affected and can be ideally electrically passivated. Optical simulations have demonstrated that the absorbed photon current density can already be increased significantly by a monolayer of SiO_2 nanospheres. We are investigating various procedures to embed the nanospheres into the high-index matrix; of these, atomic layer deposition (ALD) and sol-gel processes have proved to be very successful.

All three structuring concepts represent very promising approaches to implement cell concepts with high optical efficiency combined with low material consumption.

The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and the German Federal Ministry of Education and Research (BMBF).

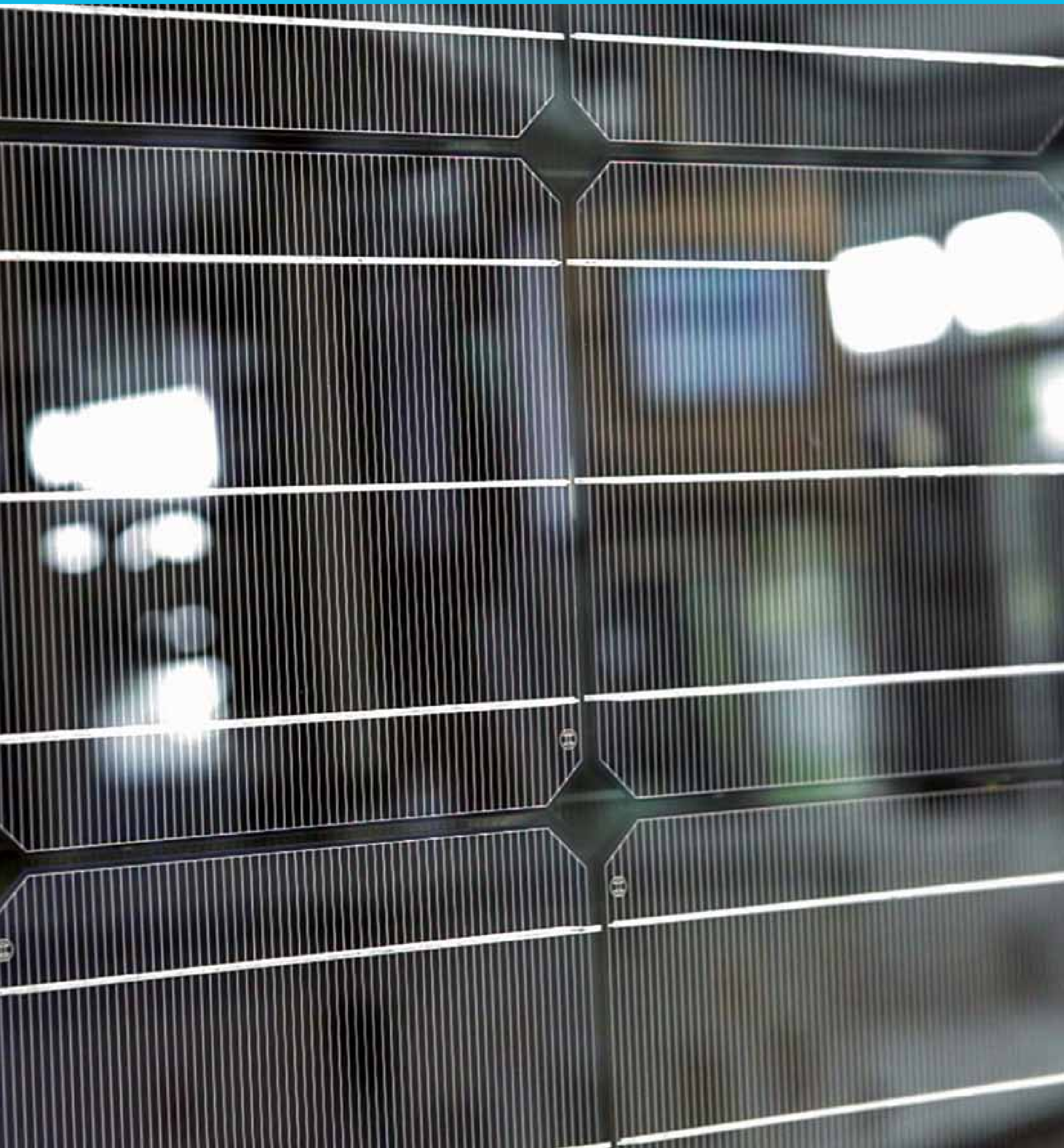


2 *Reflectance measurements of differently textured silicon substrates (without anti-reflective coatings). For both c-Si and mc-Si, the honeycomb texture prepared by NIL and plasma etching achieves excellent values, close to those for inverted pyramids.*



3 *Measured absolute increase in absorptance, caused by a back-surface grating created by NIL and plasma etching in 200 µm thick c-Si substrates. The resulting calculated increase in photocurrent is also shown.*

ELECTRICITY FROM SUNLIGHT



PHOTOVOLTAIC MODULES AND SYSTEMS

Module technology converts solar cells into durable products for safe operation in PV power plants. We support product development toward optimal efficiency, reduced costs and great reliability. We offer comprehensive services for quality control of modules and power plants from accurate laboratory measurement to monitoring in the field.

Module technology

Our new Photovoltaic Module Technology Centre (MTC) offers a wide range of processing and analytical platforms for testing materials and developing products and processes. Scientists have direct access from the laboratory to industrially relevant module formats and production volumes. A fully automated tabber-stringer serves as a reference for cell connection. Laminators with usable areas of up to 1700 mm x 1000 mm are available for module production.

Comprehensive characterisation at all stages of production makes targeted optimisation of products and processes feasible. Quality control begins with investigation of the incoming materials, from the cell through cell connectors and polymer films to glass. The quality of joints can be tested in the Photovoltaic Module Technology Centre (MTC) by solder wetting investigations, peeling tests, micrographs of polished sections and high-resolution X-ray images. The performance and integrity of a cell can be traced by characterisation at all stages from initial delivery through stringing and encapsulation to the finished module.

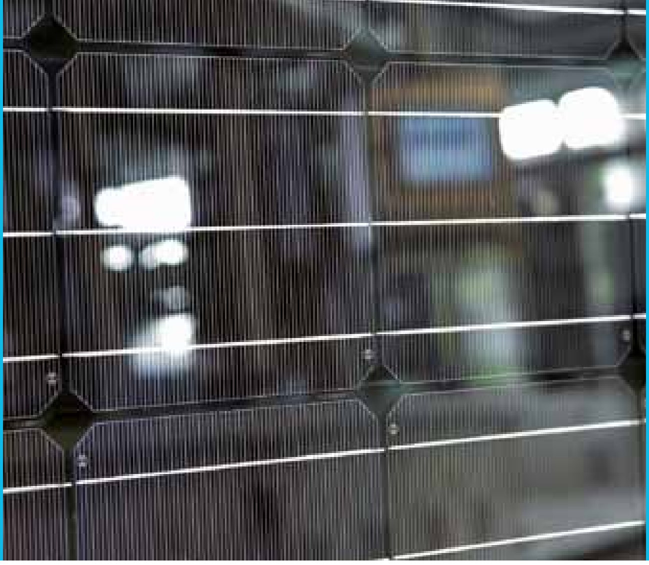
The experimental methods are complemented by numerous simulation models. They allow the loss and gain factors in the connection and encapsulation of solar cells to be analysed and provide information on mechanical loads and electrical and optical effects in the module.

Durability analysis and environmental simulation

In addition to the system efficiency, the lifetime of the components in a PV power plant is decisive in determining its profitability. We investigate the behaviour of products, components and materials over their service life. This includes materials testing and computer simulation of load tests and aging effects for various materials, components and products for solar energy conversion.

We investigate the effect of weathering with analytical methods. The aim is to recognise aging mechanisms, their causes and effects on materials, product components and entire products as early as possible. Most of these investigations apply non-destructive methods such as optical microscopy, Raman spectroscopy, Fourier transform infrared (FTIR) spectroscopy and electroluminescence imaging. The development of new or combined characterisation methods is also part of our work. One of the aims of these efforts is to replace destructive measurement methods by non-destructive methods in future.

Understanding and identifying the causes of aging is the task of environmental simulation, in which the behaviour of test objects such as PV modules is observed and documented in detail in the field at selected locations. We use sites in Freiburg (temperate climate), near the Zugspitze (Alpine climate), in the Negev desert (subtropical climate), on Gran Canaria (maritime climate) and in Jakarta (tropical climate). The work on environmental simulation is intended to allow the aging behaviour of new materials, components and products over their lifetime or service life to be better understood and predicted.



Not only the equipment of TestLab PV Modules, which has been accredited since 2006, is available for testing, but also special testing facilities for combined loads or accelerated aging.

Quality assurance for PV modules, systems and power plants

With the four phases of the Fraunhofer ISE quality cycle – yield assessment, module measurements, system testing and monitoring – we ensure comprehensive quality control of PV modules and power plants. Together with good planning and the usage of high-quality components, this is decisive for efficient operation of a PV system.

In the planning phase of a PV power plant, we draw on reliable radiation and meteorological data and simulate the system configuration exactly. Yield-reducing factors like soiling and shading are determined accurately. Strong networking within Fraunhofer ISE and international co-operation ensure that current research results are reflected in the simulation software that we develop.

For accurate measurement and characterisation of PV modules, our CalLab PV Modules offers many different types of standard and high-accuracy measurements for research, development and production. The CalLab PV Modules at Fraunhofer ISE is one of the internationally leading laboratories in this field, with its measurement accuracy of better than 2 % for crystalline modules. We calibrate reference modules for production lines and test compliance of random samples with the guaranteed power according to international standards.

Edge-sealed PV module, which we have developed at Fraunhofer ISE in co-operation with external partners. TPedge technology can reduce the manufacturing costs for modules by 35 percent due to the lower materials consumption and accelerated production process. Fraunhofer ISE supports the development of PV modules and systems toward the goals of higher efficiency values, reduced costs and greatest reliability. We offer a comprehensive package of services for quality assurance of PV modules and PV power plants, ranging from high-accuracy measurements to monitoring.

Once a PV system has started operation, comprehensive on-site analysis provides information about the quality of the system. Our spectrum of services includes visual system scrutiny, thermographic imaging and determination of the actual power supplied. Reduced power, weaknesses and deviation from technical standards can thus be detected early and suitable counter-measures taken.

Throughout the complete service life of a PV system, our customised PV monitoring offers accurate analysis of system and component efficiency. It is based on long-term experience with national and international projects and the high scientific level of our work. Fraunhofer ISE ensures optimal yields from PV modules and power plants by consistent quality assurance.

CONTACTS

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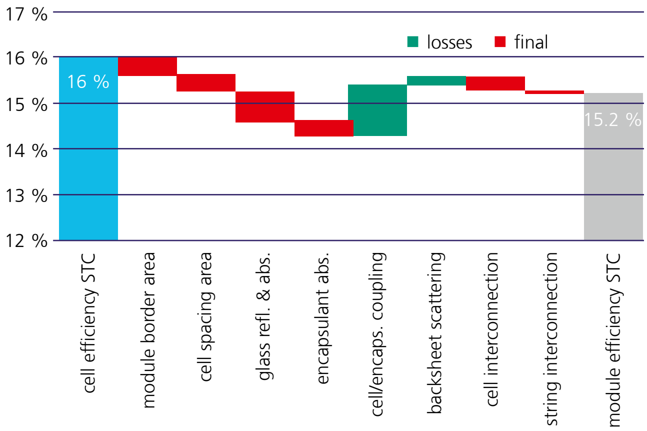
TopMod: EFFICIENT MODULE TECHNOLOGY FOR MINIMAL LOSSES IN EFFICIENCY

Within our research and development work, we have succeeded in producing a solar module with an efficiency value of 15.2 % with reference to the entire module area, consisting of sixty commercial solar cells with a nominal efficiency value of 16 %. This means a loss of only 5 % in the module efficiency relative to that of the original cell efficiency. This optimisation is based on an efficiency analysis, which quantifies losses due to encapsulation and connection in detail. The loss in efficiency was reduced by a combination of measures, particularly optical and electrical optimisation and a clear reduction in the inactive module area.

Ulrich Eitner, Ingrid Hädrich, **Marco Tranitz**, Harry Wirth

1 *TopMod detail: 60-cell module (1592 x 962 mm²).*



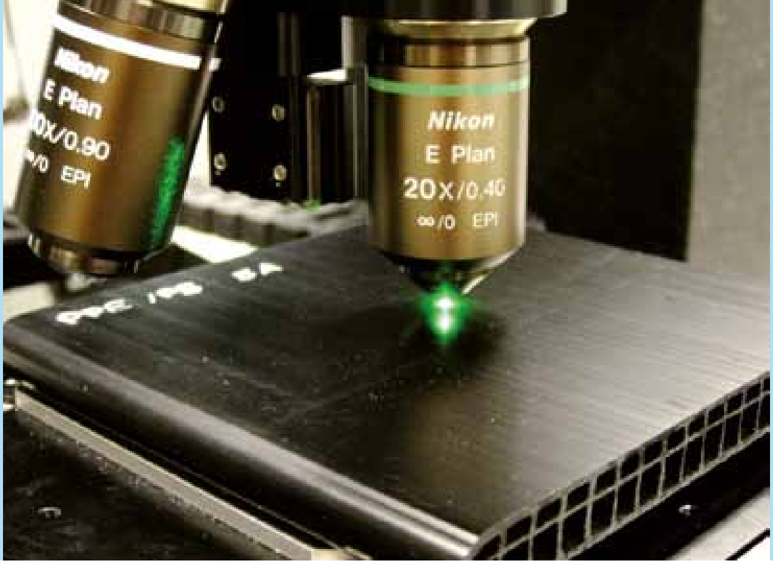
2 *Efficiency analysis with detailed breakdown of the losses and gains in efficiency.*

The development and configuration of this solar module is based on an efficiency analysis (Fig. 2), which characterises the optical and electrical losses caused by processing the cell into the finished module. High module efficiency values help to reduce the area-dependent costs of the module and subsequently the PV system – both effects reduce the levelised costs of generating PV electricity.

The solar cells used were commercially available, multi-crystalline silicon solar cells, such as are used in standard PV modules today. A glass cover with an anti-reflective coating ensured very good optical coupling of light into the module. In addition, the distance between the individual solar cells was reduced, as was also the distance between the cells and the edge of the module, so that the inactive area of the module is smaller. The connectors which join the solar cell strings to each other were positioned behind the solar cells. In order to implement this slender module border, a special method of edge sealing from insulating glazing technology was applied. In addition, special technology was used for the inter-cell connectors, which reduces optical and electrical losses. We were able to take a large step toward high-efficiency module technology with the development and construction of the optimised solar module. We have identified further potential for improving the efficiency, which we aim to exploit.

The efficiency value of the solar module was determined by the accredited CalLab PV Modules with a relative accuracy of ± 2.3 %.

The project to establish a module technology centre was supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).



AGING INVESTIGATIONS OF POLYMER SOLAR ABSORBER MATERIALS

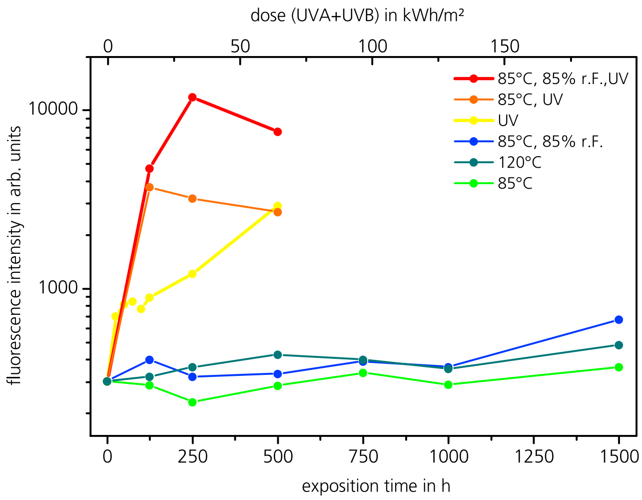
Solar absorbers currently consist of expensive materials such as copper or aluminium, of which there are only limited reserves. Using polymers as an alternative absorber material could not only offer economic advantages but also open up new possibilities for aesthetically pleasing and efficient collector designs. The resistance of various polymers to weathering was investigated with these options in mind. The samples were subjected to accelerated aging tests and outdoor exposure in Gran Canaria and Freiburg. Surface-sensitive, non-destructive test methods such as confocal Raman microscopy and atomic force microscopy (AFM) were applied to analyse the aging performance of the polymers.

Miriam Falk, Thomas Kaltenbach, Michael Köhl, **Cornelia Peike**, Christoph Stöver, Karl-Anders Weiß, Harry Wirth

With the aim of determining their suitability as solar absorber materials, multi-walled panels of polyphenylene sulphide (PPS) and a polymer blend of polyphenylene ether and polystyrene (PPE-PS) were subjected to various accelerated aging tests. The climatic parameters, temperature, humidity and UV radiation were varied systematically with the objective of setting up a model for the aging processes. In addition, samples were exposed outdoors in maritime and temperate climates (Fig. 1) and continually characterised.

Indicators for chemical and physical aging of the polymers were gained with the help of quick and simple procedures such as Raman and atomic force microscopy. These methods offer high spatial resolution in the sub-micrometre and nanometre ranges and can thus provide information on the homogeneity of the aging processes. The fluorescence which was detected by Raman spectroscopy was traced back to chromophores which are formed during polymer aging, and serves as an indicator for chemical degradation. The fluorescence intensity of the aged PPS samples revealed strong susceptibility of the investigated polymers to photochemical degradation mechanisms (Fig. 2). AFM measurements provided information on changes in the surface roughness of the samples, which can be viewed as an indicator for physical degradation of the sample surface. With the help of microscopic measurement methods, we were able to determine quantitative data to serve as a basis for numerical simulation of the aging dynamics.

1 Raman-microscopic analysis of the surface degradation of a polymer multi-walled panel (left). Outdoor exposure of polymer samples in Porto Izquierdo, Gran Canaria (right).

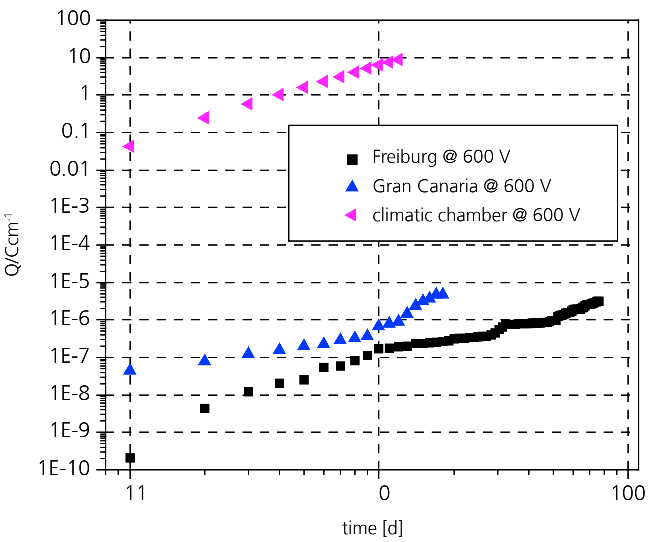


2 Fluorescence intensity determined from Raman surface scans of PPS samples exposed to different accelerated aging conditions as a function of the exposure time and the UV radiation dose.

POTENTIAL-INDUCED DEGRADATION: RAPID AND LONG-TERM TESTS

Over the past few years, the PV industry has increasingly addressed a phenomenon that causes a gradual but reversible power loss for PV generators. This phenomenon, which can occur at the negative end of a string in PV modules, is known by the name of potential-induced degradation (PID). The problem of PID should already be solved at the cell and module level so that there is no need for restrictions on the system configuration with regard to the circuit or inverters. We are developing both fast tests and long-term exposure tests to distinguish reliably between PID-resistant and PID-susceptible modules.

Stephan Hoffmann, Michael Köhl, Harry Wirth



2 *Comparison of the accumulated leakage current (charge per module perimeter length in coulomb/cm) for various climatic conditions. Different values of temperature and air humidity result in different leakage currents for the identically constructed samples.*

1 *Test field operated by Fraunhofer ISE on Gran Canaria – determination of the climatic influence on PID by continuous measurement of the power and leakage current values for the modules as well as meteorological data. In comparison to the test field in Freiburg, the air humidity and average temperatures are higher on Gran Canaria.*

Rapid tests can be used to determine the resistance of a PV module to PID but also to investigate the influence of meteorological parameters on the occurrence of PID by measurement of the resulting leakage currents. To test this, a potential difference of up to 1000 V (or the maximum system voltage) is applied between earth and the cells with an earthed, conductive film on the glass. This is done for dry room conditions or in climatic chambers under defined temperature and high air humidity conditions.

In addition, the modules are exposed outdoors at locations with markedly different climates in Freiburg and on Gran Canaria (Fig. 1) so that the long-term behaviour can be investigated. High-resolution instruments to measure current are used for this purpose, which detect even the lowest leakage currents between cells and the module frame. In addition to the leakage current as an important indicator for the occurrence of PID, the module performance data and meteorological data are also recorded. This provides a basis for comprehensive understanding of PID and later for extrapolation of the results gained in the laboratory to real exposure times of 25 years. The harsh conditions in the climatic chamber accelerate PID by several orders of magnitude and lead to an almost complete power loss for the module within a few days at app. 1 C/cm² (Fig. 2).

The project is supported by the German Federal Ministry of Education and Research (BMBF).

IS A PERFORMANCE RATIO OF MORE THAN 90 PERCENT FEASIBLE?

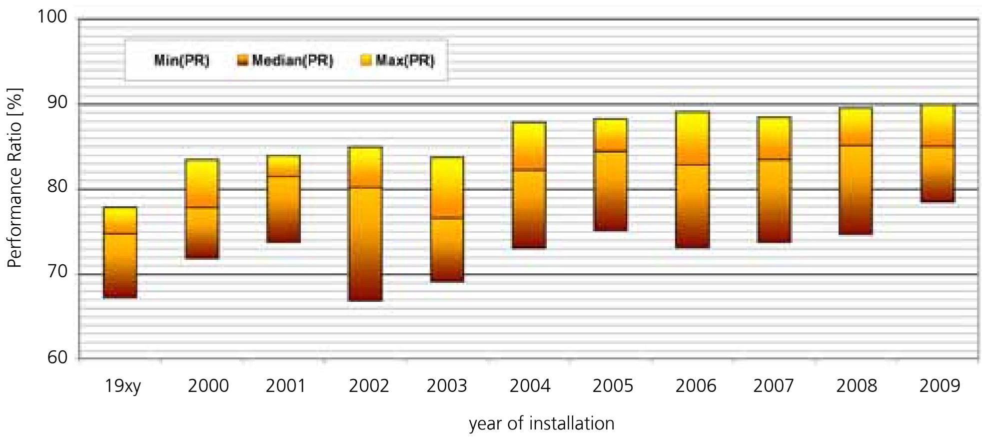
Fraunhofer ISE has been monitoring commercial PV power plants for many years as part of its PV quality cycle. We have observed that the performance ratio is still increasing, slowly but continuously. This raises a question as to how much further the quality of PV systems can be increased – where is the limit for the system efficiency?

1 *Commercial PV power plant in Raunheim (Germany), 1 MW_p, commissioned in 2011.*

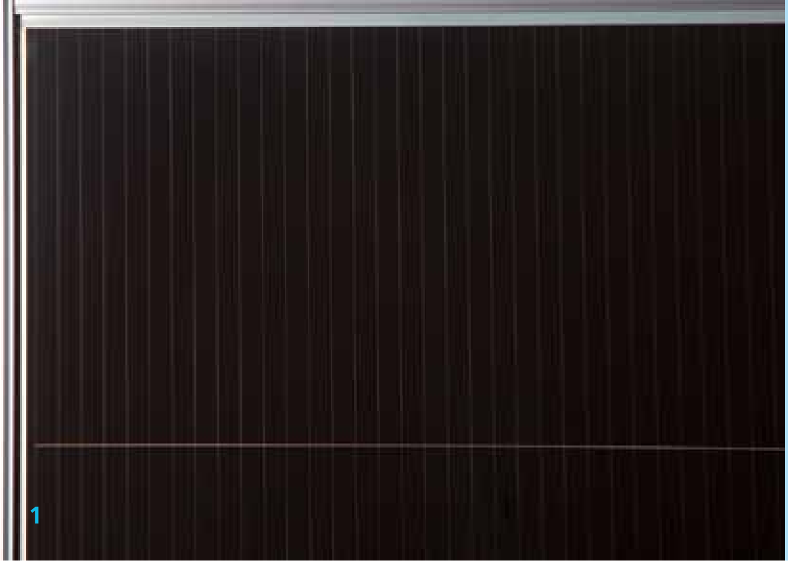
Alfons Armbruster, Klaus Kiefer, Björn Müller, Nils Reich, **Christian Reise**, Harry Wirth

The "Performance Ratio" (PR) has long served as an efficiency indicator and measure for the quality of PV power plants. In ongoing investigations, we compare the PR of about 100 recent German PV installations with that of systems from the 1980's and 1990's. Before doing so, it is important to clarify which value for the solar radiation is used to determine the PR. If the irradiance is measured with a pyranometer, the determined PR value (denoted by PR_{PYR}) is comparable with the value determined in yield assessments. If the solar radiation is measured with a silicon reference cell, the resulting PR value (denoted by PR_{Si}) is systematically 2 to 4 % higher.

For the almost 100 systems investigated, annual PR_{Si} values between about 70 % and nearly 90 % were determined for 2010, with a median value of about 84 %. The 90 % limit for PR_{Si} is missed only narrowly. However, simulation of the loss mechanisms for the ten best systems reveal further potential for optimisation, even if only by small amounts, in many areas, e.g. inverter efficiency values, cabling concepts, PV module performance at low light levels or concerning so-called "positive tolerances". Although we have not yet determined any values of PR_{Si} exceeding 90 % from the systems monitored by Fraunhofer ISE in 2010, we expect that future systems will more often display PR_{Si} values greater than 90 % for comparable temperature and radiation conditions, even when constructed of components that are already commercially available today.



2 *Median and bandwidth of PR_{Si} for almost 100 German PV systems versus the year of installation.*

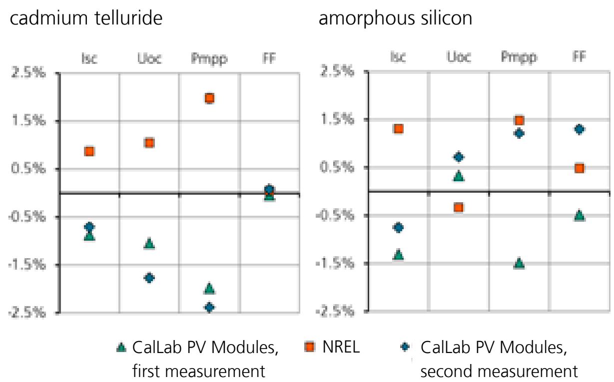


ACCURATE POWER MEASUREMENTS FOR THIN-FILM PV MODULES

The goal for power measurements of PV modules is to determine the actual power as accurately as possible. Leading measurement laboratories can do this with an uncertainty of better than ± 2 % for modules of crystalline silicon. The measurement of thin-film PV modules is currently subject to higher uncertainty due to several special properties of these modules. At Fraunhofer ISE, it was demonstrated that when certain rules are observed, it will be possible to obtain uncertainty values around ± 2 % also for thin-film PV modules in the future.

Daniela Dirnberger, Boris Farnung, Klaus Kiefer, Ulli Kräling, Frank Neuberger, Harry Wirth

1 *Thin-film PV modules can be measured at Fraunhofer ISE with an uncertainty close to ± 2 % in future.*



2 *CalLab PV Modules achieved measurement comparability of better than ± 2.5 % with NREL for two thin-film PV modules. In order to quantify changes in the module, the measurements at Fraunhofer ISE were repeated after the modules had returned from NREL. In inter-laboratory comparisons, usually four characteristic values are compared, namely short circuit current I_{sc}, open circuit voltage U_{oc}, power at the maximum power point P_{mpp} and fill factor FF.*

Thin-film PV modules differ from modules of crystalline silicon in several aspects. On the one hand, they are characterised by a different spectral response, i.e. the distribution of conversion factors for light of different wavelengths is different. On the other hand, they have other stability properties. The different spectral responses mean that the spectral mismatch factor which is needed for accurate power determination from measurements is subject to greater uncertainty, which presents the real challenge to measurement technology. However, by using a reference cell with the same limits for the spectral response, the uncertainty can be reduced to values close to ± 2 %.

The reproducibility of measurements of a cadmium telluride (CdTe) module in CalLab PV Modules was improved from 98.5 % to 99.5 %. To validate the calculated uncertainties, this type of test for the reproducibility is needed as well as comparison with measurements from other laboratories.

To do this, another challenge to measurement of thin-film PV modules must be tackled: control of their stability. By storage under well-defined climatic conditions, if necessary in combination with pre-conditioning treatment before a measurement, the modules can be stabilised to a large extent or, depending on the technology, be brought to a temporarily stable level. Nevertheless, it is not possible to control the stability completely.

CalLab PV Modules regularly conducts international inter-laboratory comparisons. In 2011, it achieved comparability of ± 2.5 % for measurements of a CdTe module and a module of amorphous silicon with NREL, the leading measurement laboratory in the USA (Fig. 2). The main cause of deviation is module instability.

1 *The PV system on the roof of the Solar Info Center in Freiburg is one of the three systems where the effect of soiling was investigated.*

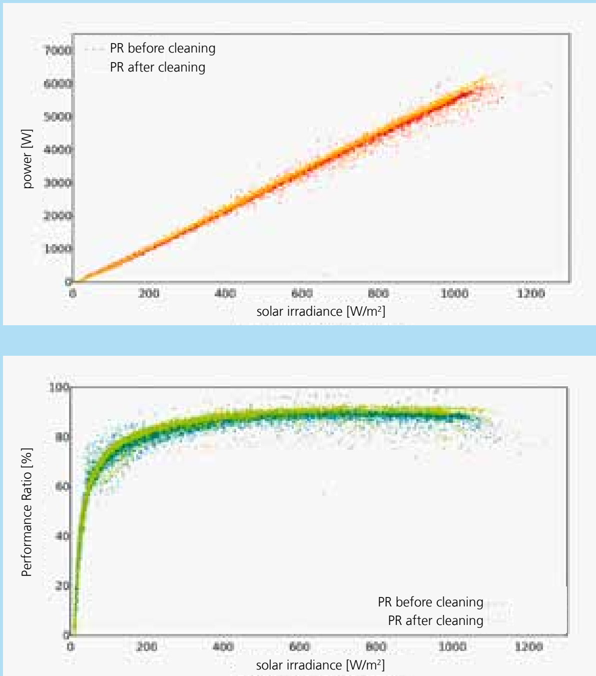
SOILING OF PV POWER PLANTS – (NOT) A PROBLEM?

How strongly does dirt on my PV system reduce the yield? This question is asked not only by many PV system operators but also by experts responsible for preparing yield assessments. However, it is not easy to give a general answer. In order to learn more about yield losses due to soiling, Fraunhofer ISE has subjected three PV systems in south-west Germany to detailed analysis.

Daniela Dirnberger, Jan Gierse, Klaus Kiefer, Anselm Kröger-Vodde, Michele Rimini, Christian Reise, Harry Wirth

The systems under investigation have been operating for between five and twelve years and have been measured in detail by Fraunhofer ISE since they were commissioned. We measure the solar radiation with a reference solar cell, the AC power that is fed by the complete system into the grid and the DC current and voltage of solar modules in one sub-array of the system. In addition, data on precipitation was recorded for this investigation, and the radiation sensor was cleaned several times a week.

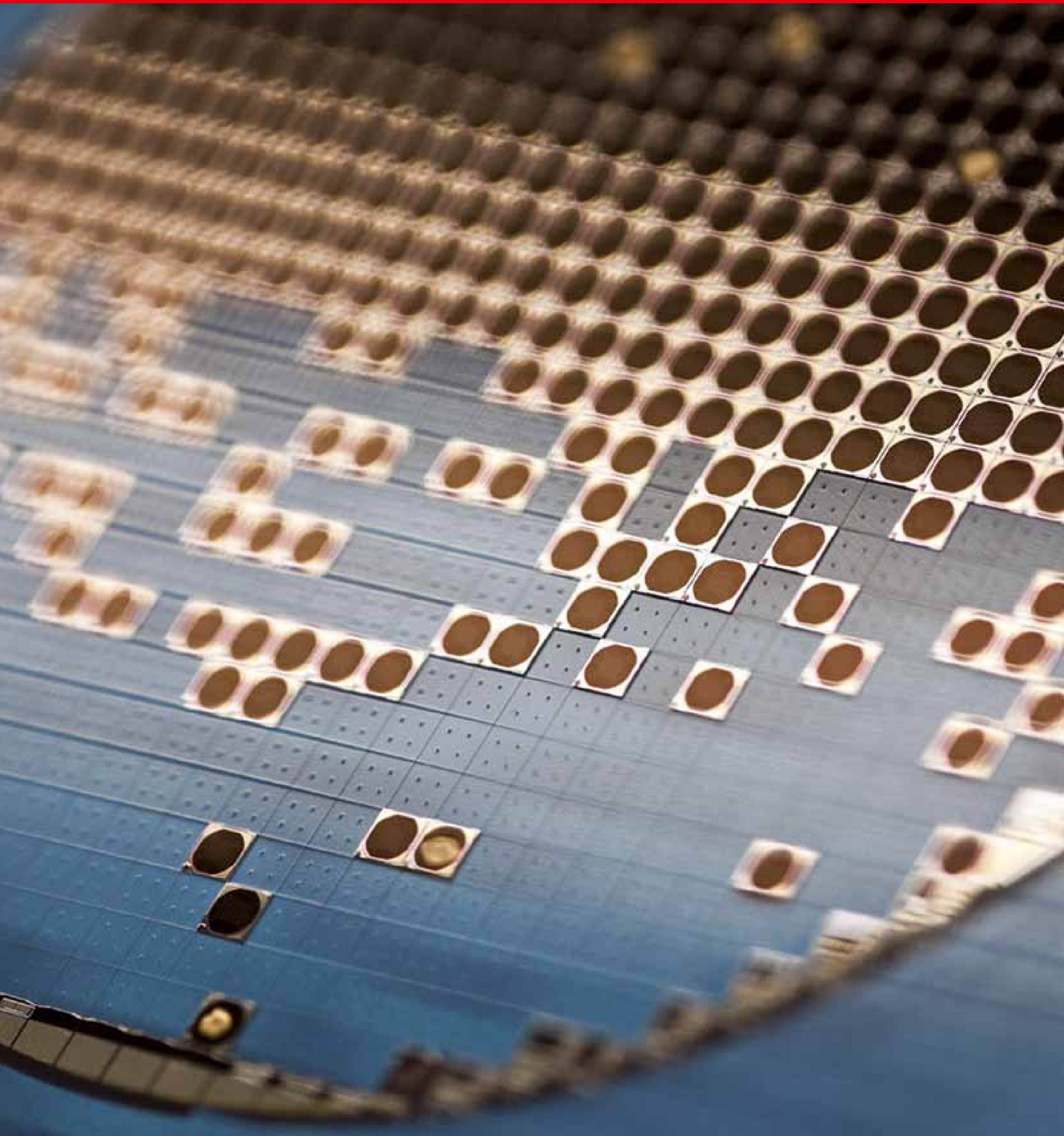
Over a period of about four weeks, the Performance Ratio (PR) of the PV system, which had not yet been cleaned, was compared with a regularly cleaned sensor. After the first complete cleaning of the system, the data were recorded for a further four to six weeks. For all three systems, a yield loss of about 1.3 % due to soiling was determined for the total period of observation on the basis of the power measurements.



2 *Comparison of the Performance Ratio before and after cleaning show the effect of soiling.*

The question concerning the time until comparable soiling has accumulated again remains open. Even under the improbable assumption that this loss can be transferred to a whole year, annual cleaning of the systems would not be worthwhile on a financial basis. In addition, the result is relevant only to systems at comparable sites: At locations where PV modules are subject to more soiling, e.g. due to agricultural or industrial activity, or in regions like deserts where more dust is present, individual analysis is needed. Fraunhofer ISE is carrying out further tests with radiation sensors and is working on concepts for general estimation of yield losses due to soiling.

ELECTRICITY FROM SUNLIGHT



ALTERNATIVE PHOTOVOLTAIC TECHNOLOGIES

Complementing the work on silicon photovoltaics (see page 58 ff), our research and development on solar cells also covers other types of photovoltaic technology: III-V semiconductors, dye solar cells, organic solar cells, concentrator technology and novel concepts for photovoltaics.

III-V semiconductors

Multi-junction solar cells, based on III-V semiconductors such as gallium indium phosphide, aluminium gallium arsenide or gallium arsenide, achieve the highest efficiency values among solar cells. The highest efficiency value attained at our Institute is 41.1 % with a concentration of 454 suns. Triple-junction solar cells of GaInP/GaInAs/Ge have already been applied successfully for years in space. We have contributed to the successful market introduction of these extremely efficient solar cells, combined with optical concentration of sunlight, for terrestrial applications. In addition to these two PV market segments, we supply III-V solar cells to niche markets such as laser power beaming, thermophotovoltaics and other specialised applications.

For applications in satellites, we are concentrating on radiation-resistant, multi-junction cells (triple to sextuple). Cells with a low mass are particularly advantageous. We are thus developing very thin cells with a thickness of only a few micrometres. To this purpose, we are developing techniques to separate the solar cell structures from one substrate and transfer them to other substrates. Among other approaches, we have applied so-called "wafer-bonding" very successfully and can create new material combinations in this way. We are continuing to work on producing III-V semiconductor structures directly on a silicon substrate by epitaxial growth. In doing so, we are investigating central questions of materials science, such as techniques to overcome lattice mismatch and stress compensation.

Dye solar cells

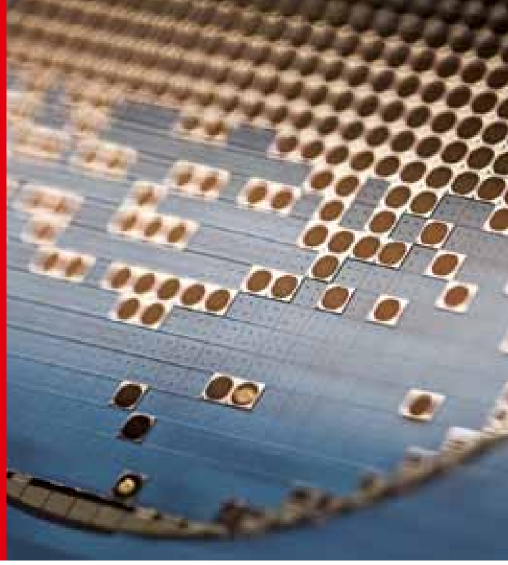
The technology for dye solar cells has developed well beyond the laboratory scale over the last few years. We were able to demonstrate that modules of dye solar cells can be produced with industrially relevant technology such as screen-printing and new sealing technology. The possibility for implementing design aspects was demonstrated in prototypes. The module durability is being tested in the laboratory and outdoors. This year, Fraunhofer ISE succeeded in producing the first prototypes in the world of dye solar modules with commercially interesting dimensions (60 cm x 100 cm) on undivided substrates. This serves as proof that the production concept can be upscaled.

Organic solar cells

Organic solar cells are particularly attractive due to the anticipated low production costs. High mechanical flexibility and low mass will open up new application fields for photovoltaics in future. We are developing new cell structures which can be produced from cost-effective materials by efficient processes. The goal of these developments is production in a roll-to-roll process. We have produced the first solar cell modules with technology that can be transferred to continuous production. Aiming for higher efficiency and longer lifetimes, we are investigating new organic semiconductors and electrodes, and the durability of encapsulated solar cells in accelerated aging tests. Lifetimes of several years have become realistic.

Concentrator technology

In ConTEC, the Concentrator Technology and Evaluation Centre, we are developing modules and systems which concentrate sunlight by a factor of > 300 for the terrestrial application of solar cells based on III-V semiconductors. Silicon solar cells are used for concentration factors of < 100. We develop and investigate soldered and adhesive connections



Wafers with multi-junction solar cells based on III-V semiconductors: These highest-performance solar cells, which have been used for many years in satellite power supplies, have now been introduced successfully to terrestrial applications by the combination with concentrator technology. The technology was included in the final round of nominations for the "Deutscher Zukunftspreis" in 2011. The highest efficiency value for triple-junction solar cells of 41.1 % was achieved at Fraunhofer ISE for a solar concentration factor of 454. Other special applications of III-V solar cells include laser power transmission and thermophotovoltaics.

which withstand temperature cycling well and are very durable. In addition, we simulate thermo-mechanical effects in concentrator modules, carry out accelerated aging tests and develop new appropriate testing procedures. We are developing concentrator receivers for the highest optical concentration factors of up to 2000. To this purpose, we use our monolithically integrated modules (MIM), in which several small cell units are connected in series at the wafer level. These cells are mounted on a water-cooled receiver, which is used in parabolic-reflector concentrator systems and in solar power towers. The FLATCON® technology, which was developed at Fraunhofer ISE, is another example of successful module development. It is now being produced successfully by SOITEC Solar in Freiburg (see page 17, Awards and Prizes, Deutscher Zukunftspreis). In current research, we are investigating the co-generation of heat and electricity with a concentrating system.

Novel solar cell concepts and photon management

We develop concepts and technology which can be applied to overcome fundamental limits on the efficiency of conventional solar cells. One concept is photon management. The aim is to raise the efficiency by splitting or shifting the solar spectral distribution before the radiation is absorbed by the solar cells. One example is up-conversion, in which unusable low-energy photons are transformed into high-energy photons. These can then be absorbed by standard solar cells. In addition, we are developing solar cells of quantum-dot materials. As their properties such as the band gap can be adjusted according to the application, silicon quantum-dot materials are very promising candidates for the production of tandem solar cells based on silicon. Further concepts include fluorescent concentrators, thermophotovoltaic systems and solar cells for wireless energy transmission with laser beams.

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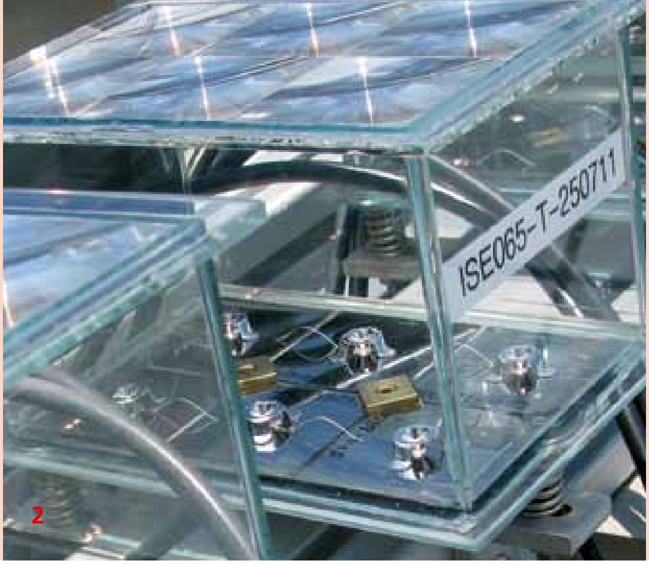
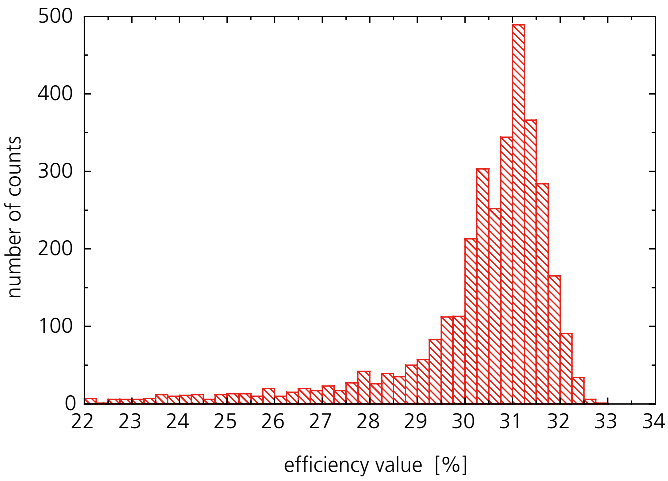


PRODUCTION PROCESSES FOR FLATCON® MODULES WITH SECONDARY OPTICS

Our FLATCON® concentrator modules based on III-V triple solar cells have achieved efficiency values of maximally 30 % under real operating conditions to date. We have not yet applied a second stage of optical concentration in our modules, so that the concept could be implemented simply and thus quickly transferred to industrial production. Now we are developing industrial production concepts for FLATCON® modules with secondary optics. Test modules reached an efficiency value of 32 % in operation under outdoor conditions.

Armin Bösch, Fabian Eltermann, Thorsten Hornung, Joachim Jaus, Gerhard Peharz, Gerald Siefer, Marc Steiner, Maike Wiesenfarth, **Andreas W. Bett**

Our research group has been developing concentrator modules for many years. One focus was the development of the FLATCON® (Fresnel Lens All-Glass Tandem Cell Concentrator) modules. A Fresnel lens concentrates sunlight by a factor of about 500 onto a 7 mm² triple solar cell. There are inevitable production tolerances in the processes to manufacture the modules and in the installation onto the tracker. In addition, the direct solar radiation is often multiply scattered in the atmosphere and forms a bright spot around the solar disc – the circumsolar radiation. With an acceptance angle of app. 0.4 °, this can lead to yield losses for our FLATCON® modules. Addition of a secondary concentrator stage is thus worthwhile. It allows such "defects" to be compensated and can also be used to increase the concentration factor. We are investigating both options and are evaluating two types of secondary optics, those based on reflection and others applying refraction. In co-operation with our industrial partner, SOITEC Solar, we developed the reflective secondary optics (Fig. 1) so far this year that now a fully industrially applicable production process is available. Millions of components can be produced with a high throughput and a good production yield. We jointly equipped a 6 kW system from SOITEC Solar with reflective secondary optics. A higher yield was proven in a direct comparison based on field measurements.



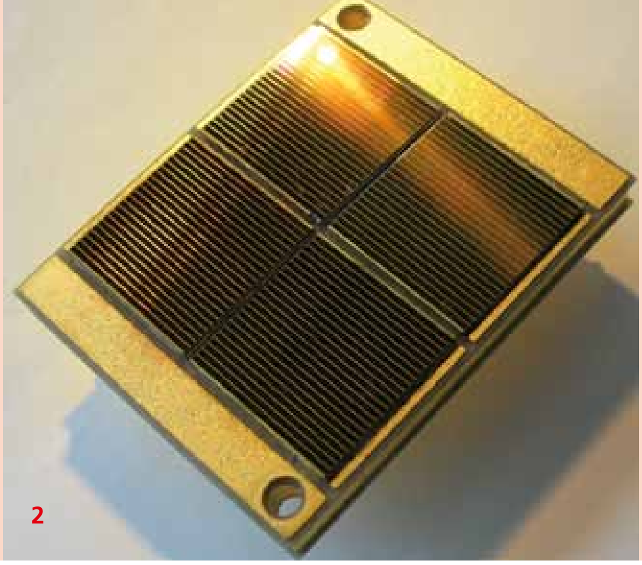
3 *Distribution of 3478 measurements of the efficiency value for a FLATCON® test module. The median value is 30.8 %, the highest measured value is 32.9 %.*

1 *Solar cell assemblies, onto which industrially produced, reflective secondary optics are mounted.*

2 *FLATCON® test module, which was mounted onto a solar tracker on the roof of Fraunhofer ISE and electrically characterised.*

We also apply these reflective secondary optical components in our FLATCON® test modules (Fig. 2). Figure 3 shows measured data from a test module. The efficiency value of 32 % was exceeded several times.

The project was supported by our industrial partner, SOITEC Solar, and the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).



CONCENTRATOR PV MODULES FOR CO-GENERATION OF HEAT AND ELECTRICITY

The total efficiency value of actively cooled concentrator modules can be increased significantly if the dissipated heat is used in addition to the generated electricity. We have already been developing actively cooled modules at Fraunhofer ISE for several years. Now we have taken an outdoor test stand into operation to scientifically investigate complete concentrator systems consisting of the optics, the cooling circuit and the receiver unit. We characterise concentrator modules in the test stand electrically and thermally at the same time. This allows us to compare different types of technology or design under real environmental conditions.

Alexander Boos, Alexander Dilger, Henning Helmers, Felix Jetter, Arne Kisser, **Maike Wiesenfarth**, Andreas W. Bett

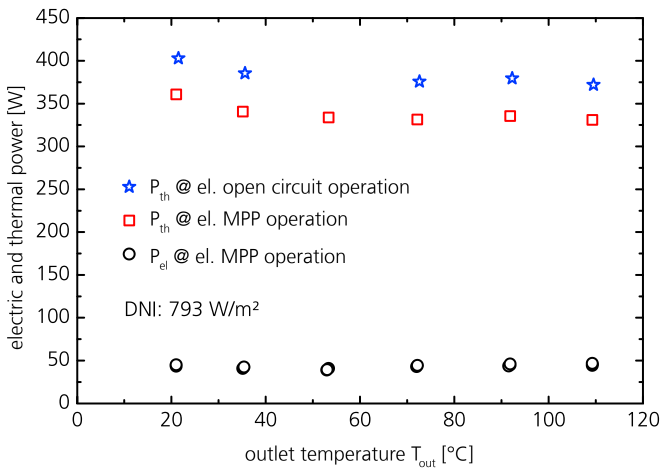
Both refractive and reflective optics are applied in high-concentration systems. When parabolic reflector systems with an area of several square metres are used, the solar cells must be actively cooled. This means that many solar cells with an area of 1-2 cm² must be packed together as closely as possible on a highly efficient cooling body and connected electrically. In the development of such compact concentrator modules (CCM), we focus on the investigation of reliability, development of production technology, encapsulation methods and new cell structures for high-efficiency, large-area solar cells (Fig. 2).

In so-called CPVT (concentrator photovoltaic and thermal) systems, thermal energy is used in addition to the generated electricity. By simply adding the thermal and electrical efficiency values, total values of 80 % are obtained. In order to verify such efficiency values, we have constructed an outdoor test stand (Fig. 1). We developed and tested CCM prototypes with different configurations. In the first high-temperature experiments in hybrid operation, we gained 331 W of useful thermal power for a cooling water temperature of 109 °C. At the same time, the concentrator solar cells supplied electric power of 46 W (Fig. 3).

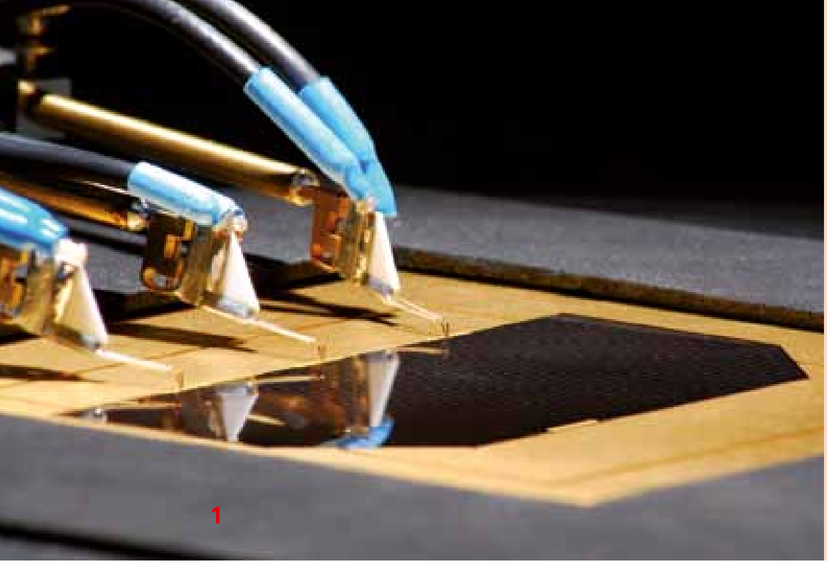
The project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and the Deutsche Bundesstiftung Umwelt (DBU).

1 *Outdoor test stand at Fraunhofer ISE with parabolic reflector optics, module and support.*

2 *Densely packed concentrator module with active cooling. Each of the four MIM (monolithically integrated module) solar cells has an area of app. 4 cm², on which a high cell voltage is obtained by series connection of 23 segments.*



3 *Thermal and electric output power P_{th} and P_{el} from the CCM prototypes (Fig. 1) versus the cooling water temperature at the outlet T_{out}. Results are shown from measurements in the hybrid mode at the electric maximum power point (MPP: black circles = electric power, red squares = thermal power) and during operation under electrical open circuit conditions (blue stars = thermal power).*



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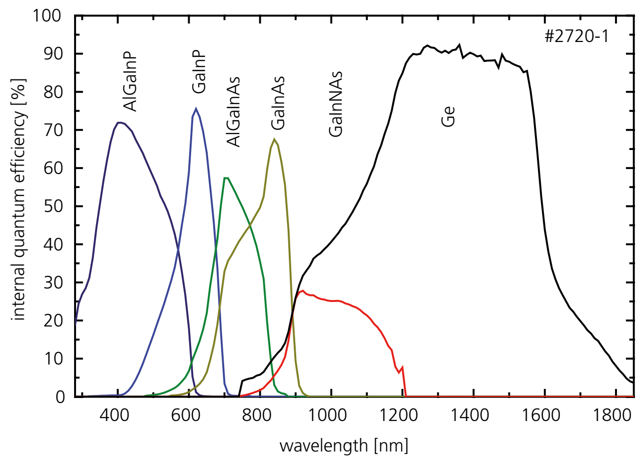


2

DEVELOPMENT AND CHARACTERISATION OF SOLAR CELLS FOR SPACE APPLICATIONS

For more than 15 years, we have been co-operating successfully with our industrial partner, AZUR SPACE Solar Power, to develop multi-junction solar cells for satellite power supplies. Today, AZUR SPACE is the largest European supplier of these special solar cells. Together, we have continually improved the efficiency of the products. Structures with stacks of three, four, five and even six pn junctions were implemented. At the same time, we worked on the development of suitable measurement instruments and procedures for characterisation and quality control of the products.

Frank Dimroth, Stephanie Essig, Elvira Fehrenbacher, Vera Klinger, Ranke Koch, Eduard Oliva, Gerald Siefer, Michael Schachtner, Manuela Scheer, Katrin Wagner, Alexander Wekkeli, Andreas W. Bett

III-V solar cells achieve the highest efficiency values for converting sunlight into electricity. Classic examples of III-V materials include gallium arsenide, aluminium gallium arsenide, gallium indium phosphide and other compounds. In contrast to silicon, III-V semiconductor compounds allow the sensitivity for certain spectral regions of the solar spectrum to be optimised by variation in the atomic composition. A multi-junction solar cell is obtained when several solar cells with sensitivity for different spectral regions from blue to infrared are stacked on top of each other. The sub-cells are optimised for a specific spectral range and the very good crystalline quality of the III-V materials used ensures the highest efficiency values. These are around 30 % for triple-junction solar cells under space conditions. We have produced monolithic solar cells with up to six pn junctions (Fig. 2), which consist of complex multi-layer stacks with up to 50 individual layers. The goal of further developments is to increase the electric power per area still further and to make the cells even more robust against bombardment by high-energy particles in space.

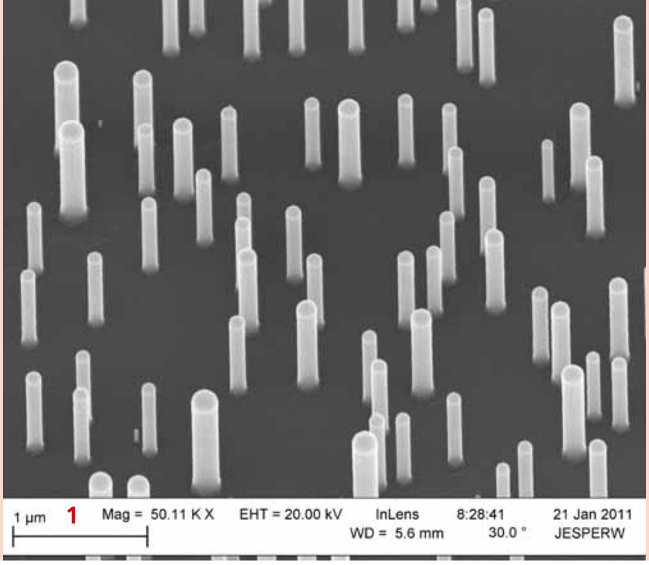
1 *Space solar cell on the measurement chuck of XSIM, a new solar simulator with 6 spectrally adjustable light paths.*

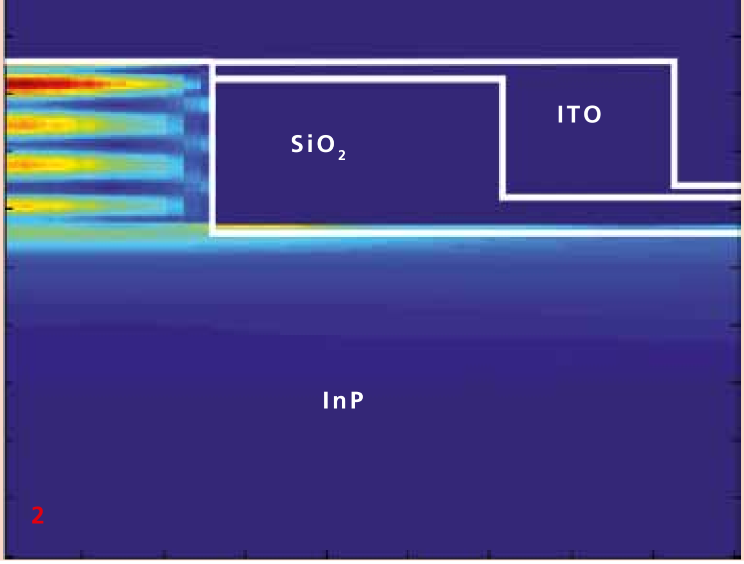
2 *Internal quantum efficiency of an AlGaInP/GaInP/AlGaInAs/GaInAs/GaInNAs/Ge sextuple-junction solar cell.*

In addition to the development of new solar cells for space applications, we are working on measurement technology for exact determination of the quantum efficiency and IV characteristics of novel solar cells when exposed to the extraterrestrial solar spectrum. A new solar simulator was constructed in co-operation with the Aescusoft company, in which the light from a xenon flash lamp is guided via six differently filtered paths to the measurement plane. Achieving homogeneity in the irradiance and the spectral distribution presents a particular challenge. The goal is to determine the performance of the solar cells with an error of less than 2 %. Furthermore, we are carrying out intensive research that will enable us to offer reliable measurements of space solar cells with three to six pn junctions.

This research is supported by our project partner, AZUR SPACE Solar Power, the European Space Agency ESA-ESTEC and the Deutsches Zentrum für Luft und Raumfahrt (DLR) /German Federal Ministry of Education and Research (BMBF).

www.III-V.de





CHARACTERISATION AND MODELLING OF NANOWIRE SOLAR CELLS

Within the EU-funded "AMON-RA" project, we are co-operating with partners from Sweden, Denmark, Austria and Germany on the development of a new generation of multi-junction solar cells, which consist of thousands of nanowires. Nanowires are tiny columns of semiconductor material, about 1 µm high and only 100 nm thick, each one forming a small solar cell. These nanostructured solar cells theoretically achieve very high efficiency values but require only a fraction of the expensive III-V semiconductor material needed for conventional cells. In future, the nanowire solar cells should be grown directly on silicon and promise to reach higher efficiency values than conventional silicon solar cells.

Frank Dimroth, Tobias Gandy, **Peter Kailuweit**, Gerald Siefer, Michael Schachtner, Andreas W. Bett

The highest efficiency values today have been achieved by multi-junction solar cells based on III-V semiconductor materials. Even so, the efficiency of these solar cells is still limited by various factors. The choice of materials is restricted, as the distance between atoms in the crystalline structure of the solar cell must be similar for all materials used to ensure high material quality and thus high efficiency.

Nanowire solar cells, which consist of many columns that are only 100 nm wide, present one approach to solve this problem. In this geometrical configuration, the crystal is extended sideways, so that the optimal semiconductor can be selected for the solar cell and the potential solar cell efficiency is increased. At the same time, the nanowires require less III-V semiconductor material than a conventional multi-junction solar cell, as they are surrounded by air or an inexpensive filling material.

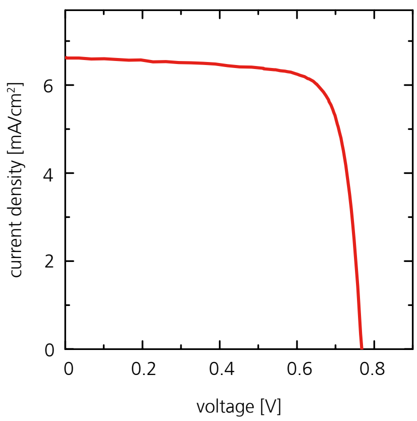
1 *Electron microscope image of nanowires, as prepared by the University of Lund and used for our solar cells. Small gold particles are used as seeds for growing the nanowire columns.*

2 *Simulated spatial distribution of charge carrier generation at a wavelength of 800 nm (cross-section through an axis of symmetry). The nanowire is covered by a shell of indium tin oxide (ITO) and quartz (SiO_2).*

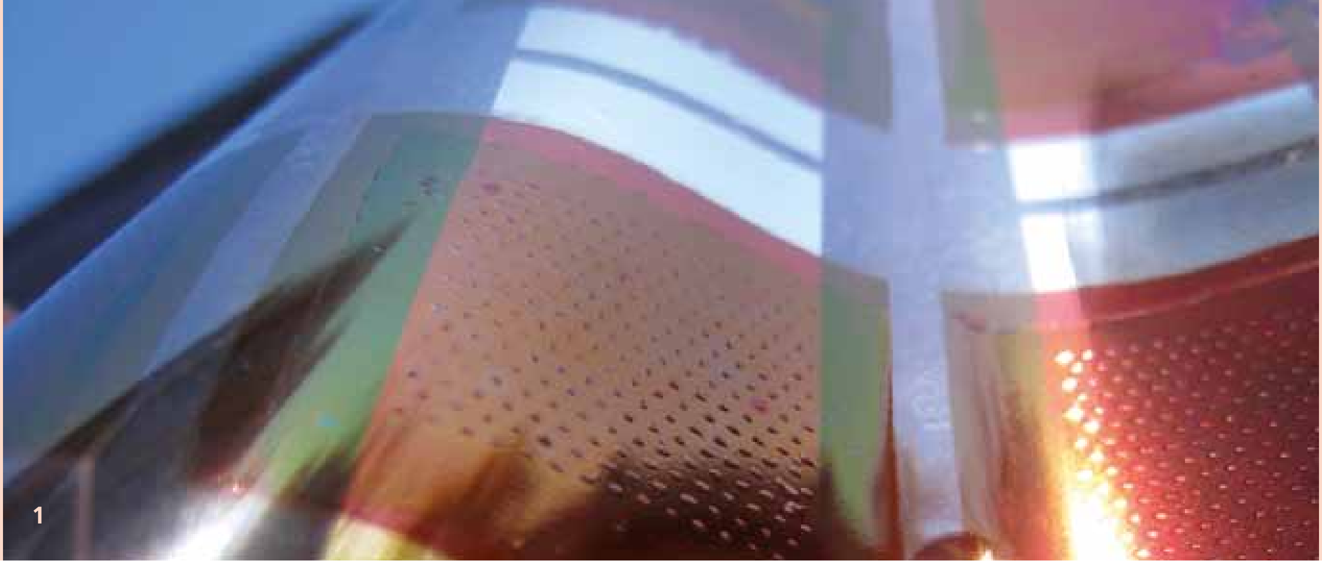
The goal of the "AMON-RA" project is to produce functional multi-junction solar cells of nanowires. We characterise the solar cells produced by our partners electrically and optically and help to understand the physical processes in these novel solar cells. We have measured initial cells with an efficiency value of 3.8 %. Furthermore, we are setting up a numerical model for optical and electrical simulation of the solar cells, with the aim of identifying optimisation potential for further development.

The "AMON-RA" project is supported by the European Union.

www.amonra.eu



3 *Current-voltage curve of a nanowire solar cell that was measured at our institute. The total efficiency of this solar cell is 3.8 %.*



DEVELOPMENT OF ORGANIC SOLAR MODULES WITH INTEGRATED WRAP-THROUGH CONTACTS

Organic solar cells have undergone dynamic developments over the past few years. The efficiency value has been increased to more than 8 % due to the diverse possibilities to synthesise organic semiconductors. This progress means that commercially relevant, industrial implementation is becoming more and more interesting. For this reason, not only the efficiency but also the lifetime and cost-effective production over large areas are gaining more attention. We are working on a module concept which can be upscaled and avoids the expensive components, indium tin oxide (ITO) and printed silver. A transparent, conductive polymer layer is used in combination with metal layers on the back surface to conduct the electricity.

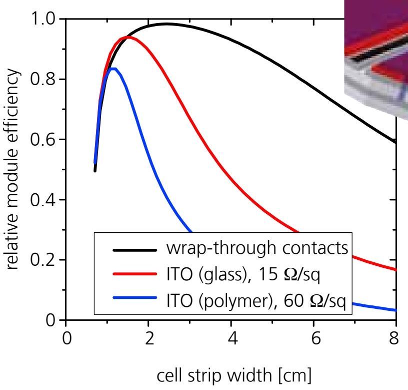
Sebastian Schiefer, Uli Würfel, **Birger Zimmermann**, Stefan Glunz

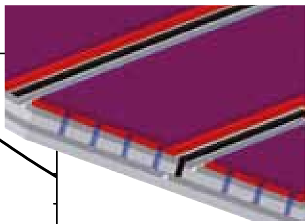
The configuration of the organic solar cell with integrated wrap-through contacts and its series connection to form a module is illustrated in Figure 2. Electricity is conducted through vias in the substrate to the back surface, which is covered completely by a metal layer. This concept is similar to the "metal wrap-through (MWT)" structures which have already been successfully applied for silicon solar cells. With this structure on organic solar cells, very cost-effective materials like aluminium or copper can be used for both electrodes. Compatibility to roll-to-roll processing is ensured by the use of flexible substrates. The graph in Figure 2 shows the result of simulations, in which the relative module efficiency value was determined as a function of the cell strip width. Compared to modules based on ITO, the wrap-through concept not only saves costs but also offers the potential for higher efficiency. The significantly better conductivity of a continuous metal layer rather than a transparent electrode makes it feasible to increase the distance between cells for series connection and thus reduce losses due to inactive areas in the module.

Experimentally, we were able to achieve efficiency values of 3 % over an area of 2.2 cm² using a standard material system of poly(3-hexyl thiophene) and [6,6]-phenyl C_{61} butyric acid methyl ester. This result is very promising, as values of about 3 to 4 % are usually obtained with these materials. Filling the vias with the transparent organic conductor offers potential for further improvement. At present, significant series resistance still arises, which causes a reduction in the fill factor.

The work is supported by the European Union.

1 Detail of an organic solar cell with integrated wrap-through contacts.





2 The wrap-through contacts and the series connection are shown schematically at the right. The graph to the left shows the relative module efficiency value as a function of the cell strip width for the wrap-through cell concept compared to that for modules with ITO electrodes. A loss zone width of 1 mm was assumed for the series connection.

DYE SOLAR MODULES – PHOTOVOLTAICALLY ACTIVE ARCHITECTURAL GLAZING

Dye solar cells represent a type of photovoltaic technology which is still young but has recently developed well beyond the laboratory scale. Upscaling always presents a major challenge in the development of new photovoltaic technology – the step from laboratory dimensions to industrial implementation. By producing the first dye solar modules in the world on a continuous substrate with dimensions of 60 cm x 100 cm, the researchers at Fraunhofer ISE have successfully taken an important step.

1 *The first large-area dye solar module on a single substrate (60 cm x 100 cm) in the world, which was produced at Fraunhofer ISE.*

2 *Dye solar modules can be designed to be either opaque or transparent and thus present interesting objects for application in building-integrated photovoltaics.*

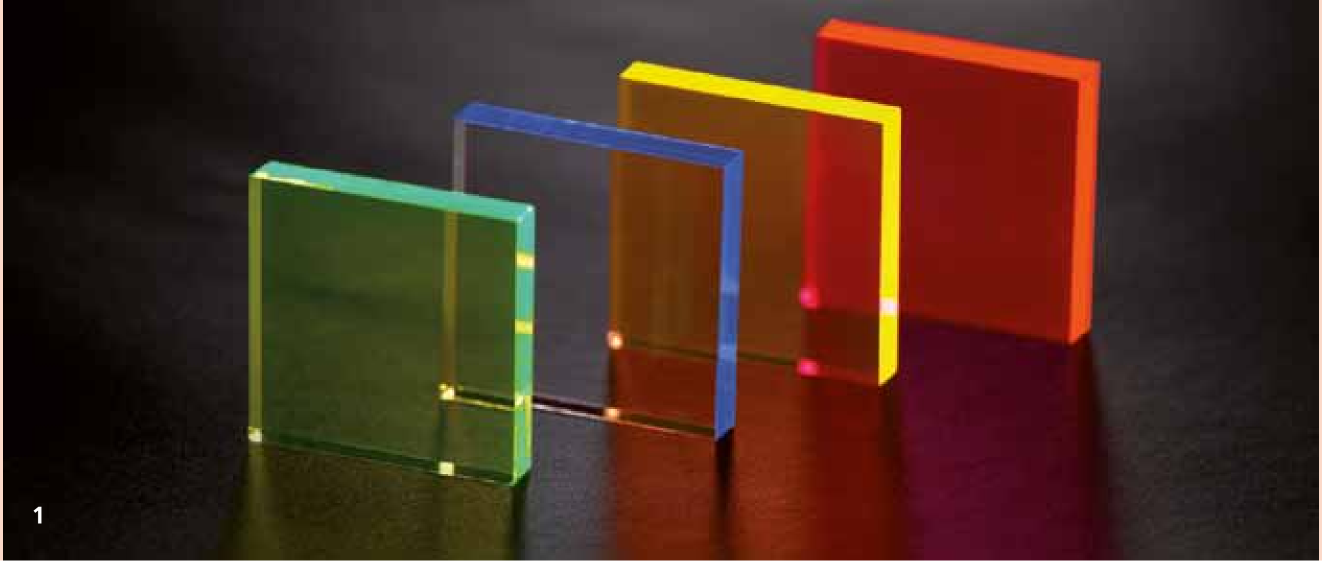
Katarzyna Bialecka, **Henning Brandt**, Katrine Flarup-Jensen, **Andreas Hinsch**, Joanna Kaminska, Ramiro Loayza Aguirre, Welmoed Veurman, Stefan Glunz

In contrast to conventional solar cells based on inorganic semiconductors, dye solar cells employ an organic dye to convert light to electricity. The modules are prepared by simple screen printing and are sealed with glass frit in a thermal fusing step. The series connection is also made in this step. These processes are comparable with production processes as are applied e.g. in the glass industry. The recently produced modules with the large area of 6000 cm^2 thus represent an important step toward cost-effective production of dye solar modules. They are intended for integration into the building envelope.

In the module concept that was developed at Fraunhofer ISE, groups of twelve solar cells are each connected internally in series. At present, an efficiency value of 7.1 % is achieved for 10 cm x 10 cm modules, which were prepared with the same method. An increase in the solar efficiency value is to be expected in the near future due to improvements in the printing technology.

Our current work is concentrating on implementing the process steps for industrially relevant conditions and developing methods for quality control. The production of dye solar modules opens up new sales markets for nanoparticles, screen-printing pastes and fine chemicals. For this reason, we are collaborating with enterprises from these sectors which are interested in co-operation on manufacturing and marketing dye solar cells. The production of dye solar cells can be integrated into existing sequences for processing flat glass.

The work was supported within joint research projects by the German Federal Ministry of Education and Research (BMBF), the Baden-Württemberg Ministry for the Environment, the Baden-Württemberg-Stiftung and the European Commission.



NEW SIMULATION MODELS FOR BETTER PHOTON MANAGEMENT

The optical pathway and spectral composition of light can be influenced favourably by photon management. In this way, fundamental limits on the efficiency of conventional solar cells can be overcome. To this purpose, we are investigating up-conversion of low-energy photons, which would otherwise pass through the solar cell unused. Photon management can also be applied to concentrate light using advanced fluorescent concentrators, so that the required area of solar cells and thus the levelised cost of electricity can be reduced.

Benedikt Bläsi, Stefan Fischer, Judith Frank, Johannes Gutmann, **Jan Christoph Goldschmidt**, Martin Hermle, Barbara Herter, Stefan Janz, Janina Löffler, Marius Peters, Janina Posdziech, Tim Rist, Heiko Steinkemper, Stefan Glunz

1 *Different fluorescent concentrators, which guide light from different spectral ranges to the edges of the concentrators.*

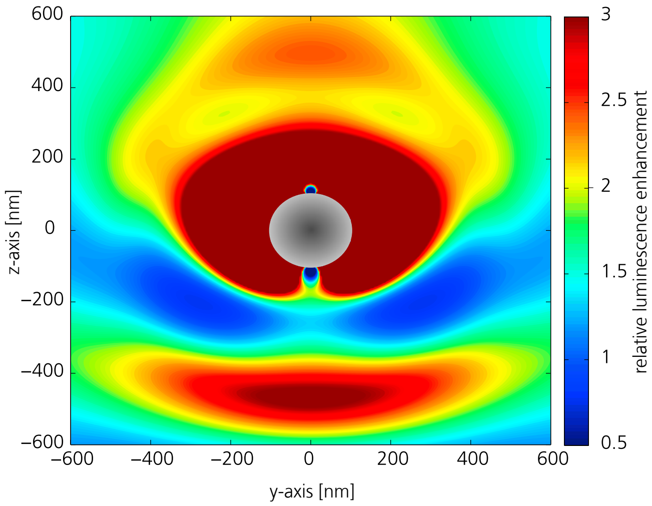
Around 20 % of incident solar energy is lost because silicon solar cells cannot absorb photons with energy less than the silicon band-gap energy. These photons are converted by up-conversion into higher-energy photons, which can then be used in standard solar cells. In order to increase the efficiency of this process, we are investigating several concepts. Combination with a second luminescent material broadens the spectral range which can be used. Combination with metal nanoparticles improves the efficiency of the up-conversion process and spectrally selectively reflecting photonic structures ensure that the individual photons are used in that region of the system where they can be converted with the greatest efficiency.

Development of such complex systems can succeed only if based on good modelling of the relevant physical processes. Thus, a model was developed at Fraunhofer ISE which describes the up-conversion in erbium by rate equations and which can be extended in principle to other rare earths. Together with project partners, we have combined this model with calculations of the properties of metal nano-particles. This can be used to calculate how metal nanoparticles enhance the efficiency of up-conversion (Fig. 2). Combined with simulation-assisted optimisation of bifacial silicon solar cells for application in up-conversion and theoretical description of photonic structures for spectral management, it is now possible to optimise the individual components and the entire system.

Beyond this work, the infrastructure was established at Fraunhofer ISE to comprehensively characterise both individual components and complete systems consisting of up-converters and solar cells. The equipment includes calibrated photo-luminescence measurement facilities and solar simulators with concentrated light.

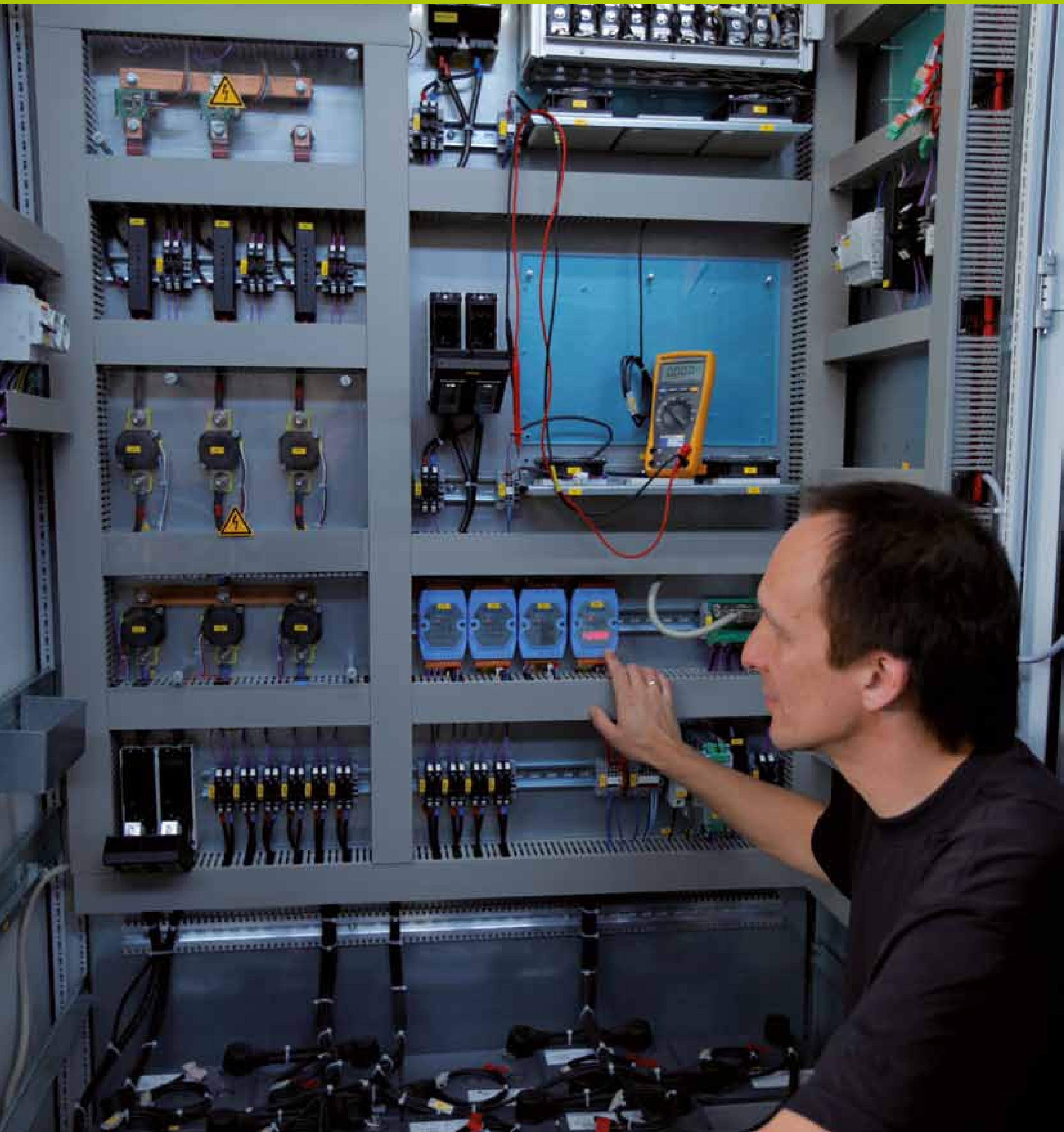
Fluorescent concentrators can concentrate both direct and diffuse solar radiation or light. This allows the solar cell area to be reduced, accompanied by cost savings. Fluorescent concentrators are particularly interesting for indoor applications and for building integration due to their attractive appearance. For commercial applications, the efficiency of fluorescent concentrator systems must be improved further. This is feasible with photonic structures which enhance light-guiding. Infrared-active semiconductor nanoparticles extend the spectral range which can be used into the infrared. We describe the relevant phenomena in the nanometre range by finite difference time domain (FDTD) simulations. For the optical description of complete components, we apply a Monte-Carlo simulation which we developed specially for this purpose. Modelling on fluorescent concentrators is also complemented by extensive experimental work.

The work is supported by the Deutsche Forschungsgemeinschaft, the German Federal Ministry of Education and Research (BMBF) and the European Union.



2 *Enhancement of emission from up-conversion near a metal nanoparticle. This was calculated using a special rate equation model for the up-converter material. The emission can be enhanced by a factor of three in certain regions.*

SUPPLYING POWER EFFICIENTLY



RENEWABLE POWER SUPPLY

In 2011, the share of electricity generated in Germany from renewable sources exceeded 20 percent for the first time. This share should increase to 80 percent by 2050. The main growth is in the wind energy and photovoltaic sectors. As the electricity generated from both sources fluctuates according to the weather conditions, further expansion in these sectors will demand major adaptation of the energy supply system. In order to cope with the associated technical, ecological and economic demands, we are developing new concepts and components based on modern communications technology for energy management of distributed generators and loads in the distribution grid. Involvement of the electricity customers with regard to usage behaviour, consumption visualisation and efficient billing methods (smart metering) are playing an increasingly significant role in this process.

Storage of electricity to compensate for differences between supply and demand is a particularly important aspect when the amount of electricity generated from renewable sources increases. Storage solutions are also needed in autonomous, off-grid electricity systems and for electric vehicles. Thus, we are working intensively on developing and optimising battery systems for stationary and mobile applications. Our work concentrates on increasing the performance and storage capacity, improving operation management strategies and developing control systems for all common types of battery technology.

The development of photovoltaics is the most dynamic of the renewable energy sectors. Already at the end of June 2011, it accounted for 3.5 percent of the electricity generated in Germany. To maintain this market growth also now that feed-in payments are decreasing, the costs for the systems technology must be reduced further. This applies particularly to inverters to feed photovoltaic electricity into the grid, a product sector in which German manufacturers continue to dominate the market. Nevertheless, there is still considerable potential for increasing efficiency and reducing costs, which can be exploited with new circuit designs, digital controls technology, advances in power semiconductor components and passive components. In addition, as the share of electricity that is generated from fluctuating sources and fed into the grid increases, inverters will have to provide more and more grid-stabilising features in future. To this purpose, we offer specialised know-how for the entire power spectrum up to the MW range in the fields of circuit design, as well as dimensioning and implementing analog and digital controllers. Beyond this, as a new service to our clients, we carry out all tests demanded by the new grid-connection regulation for transformers with power ratings up to more than 1 MW.

Around two thousand million people in rural areas, innumerable technical systems for telecommunications, environmental measurement technology or telematics, and four thousand million portable electronic devices all have one feature in common: They require off-grid electricity. Increasingly, regenerative energy sources or other innovative energy converters are being used to supply it. An increasing share of the photovoltaic modules sold world-wide is used in these markets, some of which are already economically viable without external subsidies. In addition, there is an enormous market for decentralised water desalination and purification technology based on renewable energy sources. For this broad spectrum of applications, we develop concepts, components and systems for off-grid power supplies based on photovoltaics, fuel cells, wind energy and hydroelectricity.

In future, vehicles will run partly or completely on electricity and draw their energy from the grid (electric and plug-in vehicles). Fraunhofer ISE is working at the interface between the vehicles and the grid on concepts for an environmentally acceptable power supply and optimal integration of the vehicles into the electricity grid. Together with partners from the car and power industries, the Institute is developing components for energy management and for bi-directional energy transfer between vehicles and the grid, as well as universal metering and billing systems.

For solar power generation on a large scale, predominantly for application in southern countries, Fraunhofer ISE is working on technology for solar-thermal power stations.

The facilities for our work on renewable power generation include:
- power electronics laboratory with modern equipment and software for power up to 1 MW
- laboratory for inverter certification (fault ride-through (FRT), efficiency value measurement, power quality, etc.)
- development environments for micro-controllers, digital signal processors (DSP) and embedded systems
- measurement laboratory for electromagnetic compatibility (EMC)
- laboratory for information and communications technology
- smart metering laboratory
- measurement and calibration laboratory for solar modules
- outdoor test field for solar components
- battery laboratory for development and testing from the low-power to automotive range
- lighting laboratory
- test stands for fuel cells operating with hydrogen and methanol
- spatially resolved characterisation of fuel cells
- testing and development laboratory for drinking water treatment systems

Test stand for a hybrid battery system consisting of lead-acid and lithium-ion batteries. In particular, the test rig can be used to investigate switching processes between the various types of battery technology, as well as for the development of battery modules and battery management systems.

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1

BIDIRECTIONAL GRID INTEGRATION OF ELECTRIC VEHICLES

The large share of electricity generated from renewable energy sources in future will result in a fluctuating supply of electricity. This requires new procedures for demand-side management and the application of storage technology. Electric vehicles of the future could adapt their charging profile to the availability of renewably generated electricity in the grid, on the one hand. On the other hand, they could make their storage capacity accessible for grid-supporting measures as a part of vehicle-to-grid concepts. In the VW-E.ON fleet experiment, Fraunhofer ISE has designed and demonstrated intelligent charging infrastructure, which will control the charging processes for future electric vehicles and adapt it to the supply of renewably generated electricity.

Eduard Enderle, **Robert Kohrs**, Michael Mierau, Christof Wittwer, Günther Ebert

The core of the charging management is an optimisation algorithm which is implemented in the mobile Smart Meter (mSM) integrated into the vehicle. This optimisation algorithm prepares a cost-optimised charging schedule, which adapts the input and output of electricity to the fluctuating supply of renewably generated electricity, making use of a programmed battery model and taking the departure time entered by the user into account. The stimulus signal used to communicate the state of the energy supply is a dynamic electricity tariff with time-dependent values for every quarter hour.

1 *View of the intelligent charging stations that were developed as part of the VW-E.ON fleet experiment.*

During peak load periods, grid-supporting services can be demanded at short notice by a tariff update. A pre-defined sector of the current tariff table is overwritten with new tariffs, causing the vehicle to react by shifting its load or feeding electricity into the grid. Bottlenecks in the local grid situation can be taken into account by communicating a grid-determined power limit to the vehicle for a defined period of time. The vehicle reacts with a new charging schedule, which is now based on the reduced power limit. A gentle load disconnection can also be implemented by withdrawing permission to connect to the grid; in this case, the vehicle changes to an idle mode and does not resume charging until connection permission has been granted again.

Vehicles are integrated into the grid via the intelligent charging station of Fraunhofer ISE, which authenticates the vehicles, communicates the tariffs and acquires the energy values and inputs for optimisation. The acquired data are presented in detail for the vehicle driver via graphs on a web portal, visualising the added value of charging according to the cost-optimised charging schedule.

FLEXIBLE OPERATION OF DISTRIBUTED GENERATORS IN A SMART GRID

Controllable distributed generators in the electricity distribution grid can contribute decisively toward balancing supply and demand and providing grid services as the share of fluctuating, renewably generated electricity increases. By intelligent operation management of smaller combined heat and power (CHP) co-generation systems, it is possible to operate these aggregates in the electricity-heat-led mode and to adapt the electricity generation as required to the varying electricity demand. We develop hardware and software solutions for application, and test these by simulation, in the laboratory and in field tests. In addition, we develop business plans and describe application cases and legislative boundary conditions for practical implementation.

Thomas Erge, Dennis Freiberger, Raphael Hollinger, Christof Wittwer, Günther Ebert

Restructuring of the electricity supply in Germany is associated with expansion of distributed generation. Highly efficient CHP plants form one part of this concept, which have been primarily operated to meet the heating demand up to now. Electricity was generated almost as a waste product. Demand-oriented electricity generation, which takes the thermal restrictions into account, becomes feasible by the integration of storage units. Prediction of both the thermal and electric demand is then the basis for operating the CHP plant.

Application of our distributed software and hardware framework allows CHP plants to be operated in a mode which optimises the match between supply and demand.

1 The SmartEnergyLab at Fraunhofer ISE is equipped with a complete range of regenerative and efficient, electrical and thermal generators and storage units suitable for future free-standing houses and medium-density housing. By modelling and integrating all thermal and electric energy flows, we offer a platform to analyse, evaluate and develop Smart Homes and Smart Grid technology for the distribution grid.

Various pilot projects are currently running to demonstrate how this functions in practice. Together with the city utility in Wuppertal and the University of Wuppertal, we are optimising the operation of small CHP plants in medium-density housing. The CHP plants are operated in an economically optimised mode based on tariffs which reflect the demand in the local building and distribution grid as well as the global demand.

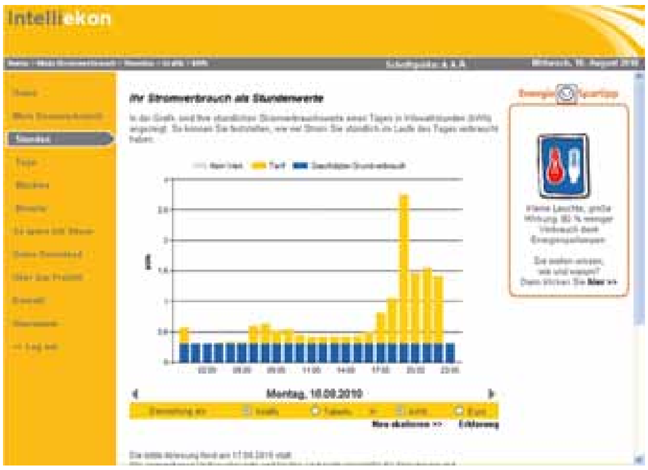
We have implemented a different solution in the e-Energy pilot project, "eTelligence – Modellregion Cuxhaven". Here, CHP plants sell their electricity on a regional market, where not only the supply of active power but also options for innovative auxiliary services (e.g. reactive power) are analysed.

In our SmartEnergyLab, we model technical scenarios and operation management scenarios in a unique combination of simulation and reality. In this way, we are able to ensure the suitability of components for intelligent operation management in Smart Grid before they are applied in the field.

ENERGY EFFICIENCY DUE TO SMART ELECTRICITY METERS

The German policy to mitigate climate change has included smart electricity meters as instruments to increase energy efficiency and as important components for load management in intelligent electricity grids. Intelligent measurement equipment is part of the infrastructure used to systematically match generation and consumption to each other. We develop solutions and test these by simulation and experiments in the laboratory and the field. In addition, we accompany field experiments with sociological and technical support to analyse effects on consumer behaviour and to support the development of new products by cost-benefit analyses from energy economics.

Dorika Fleissner, **Sebastian Gölz**, Thies Stillahn, Christof Wittwer, Günther Ebert



2 *Example (screenshot) of a web page from the "Intelliekon" project. Fraunhofer ISE offers innovative solutions and sophisticated accompanying research for Smart Grids, independent evaluation of the energy-relevant effect for private and commercial customers and energy-economic assessment of potential.*

1 *Smart meters can help to save electricity. In the "Intelliekon" project, consumer response to feedback from the electricity meters was one of the aspects investigated.*

The recent introduction of smart meters was expected to help households to save electricity. Fraunhofer ISE co-operated with research partners to investigate whether electricity can really be saved by feedback on electricity consumption via Internet or a conventional letter on paper. In a field experiment involving more than 2000 households, Fraunhofer ISE investigated the response to feedback and gained valuable insight on electricity saving due to smart meters. The feedback offer alone was sufficient to reduce electricity consumption by 3.7 %. Households with a tariff depending on time of use achieved additional savings of 6 %; the load shift amounted to only 2 %.

Particularly the results on the time-dependent tariff show that suitable stimulation systems should be pursued further to encourage the involvement of households when the German power supply is restructured. New product options for utilities, service providers and owners of PV systems can be accessed by linking innovative tariffs to the bill-payer's own electricity generation by PV or combined heat and power plants. With its interdisciplinary research, Fraunhofer ISE is identifying ways to support efficiency campaigns and load management by services, e.g. load recognition for different categories of appliances, and to highlight new product options.

www.intelliekon.de
www.openmuc.org

STUDY ON STORAGE FOR A REGENERATIVE ELECTRICITY SUPPLY

Due to the increasing share of renewably generated electricity from photovoltaics and wind turbines, there is considerable discussion in Germany and around the world on the choice and quantity of storage units for electricity which need to be integrated into the public electricity grid to compensate e.g. for periods of overcast weather or little wind. On commission to the International Electrotechnical Commission (IEC), Fraunhofer ISE co-operated with the Japanese utility, Tepco, to prepare the IEC White Paper entitled "Electrical Energy Storage". This study describes the tasks, the types of technology, the need for standardisation, current and future application cases and markets for electricity storage around the world.

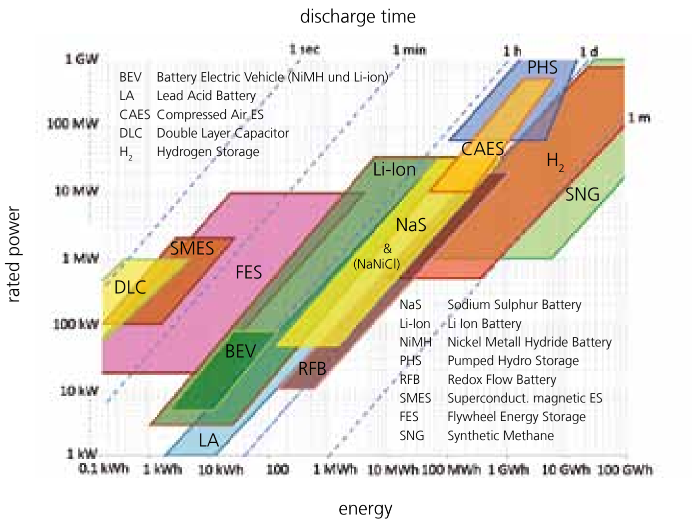
Georg Bopp, Matthias Merkle, Tom Smolinka, Simon Schwunk, Günther Ebert

Today, electricity storage units in electricity grids compensate short (0.1 s–15 min) and medium (15 min–12 h) peaks on both the generation and consumption sides. Up to now, mainly the rotating mass of electric generators, pumped hydroelectric systems and very occasionally lead-acid, sodium-sulphur and lithium-ion batteries have been used for this purpose. As increasing numbers of photovoltaic and wind energy systems are installed, fluctuation on the generation side is increasing. Several recent studies have proven that more electric storage capacity will be needed throughout the world to balance out these fluctuations.

For example, an electric storage capacity for up to 8000 GWh is predicted for Germany in 2030 with a regenerative electricity share of 60–80 %. This exceeds the storage capacity of current German pumped hydroelectric systems by a factor of 200. However, further extension in Germany is possible only to a very limited extent due to topographical restrictions.

1 Cell stack of a vanadium redox-flow battery.

2 Lithium-ion battery module with (electronic) battery management.



3 Typical values for power, energy and discharge times for various electricity storage units. Unlike sodium-sulphur and redox-flow batteries, the lithium-ion battery is suitable for both short-term and medium-term storage.

Storage alternatives are offered by compressed air, hydrogen or synthetic methane, particularly in the GWh to TWh range. In these three approaches, the relevant gas is stored in underground caverns. Furthermore, the natural gas network, with its nominal storage capacity of 200 000 GWh, already offers the potential to add large quantities of hydrogen or methane that exceed the demand predicted for 2030. For short-term and medium-term storage, pumped hydroelectric systems and many additional electrochemical storage units such as sodium-sulphur, lithium-ion or redox-flow batteries will be required.

1

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LITHIUM-ION BATTERY SYSTEM FOR ELECTRIC VEHICLES

The future commercial success of electric vehicles depends critically on the performance and quality of the batteries used in the vehicles. Selection of the right type of cells – today usually lithium-ion cells – is only the first step. The battery system design is equally important, consisting of many connected cells which must be integrated into the vehicle, mechanically, electrically, thermally and with regard to communications. There is need for a crash-resistant casing, an efficient cooling system and a monitoring system which is optimised for the cell technology and the application. The goal is to keep the energy consumption for these auxiliary functions as low as possible, so that they do not significantly reduce the action radius of the vehicle.

Nils Armbruster, Stefan Gschwander, Max Jung, Stephan Lux, **Simon Schwunk**, Matthias Vetter, Günther Ebert

Within the context of "Fraunhofer Systems Research on Electromobility", Fraunhofer ISE managed the "Battery System" sub-project, in which a new battery system was developed and constructed in co-operation with other Fraunhofer Institutes.

The control electronics for monitoring and control is the intelligent component of this battery system and is based on a decentralised concept. Each module has a small, energy-saving circuit board which monitors the cell voltages and temperatures. The circuit recognises cell defects such as overcharging and detects the state of each individual cell. This is done, e.g. in aging diagnosis, with accuracy of better than 1 % over a wide temperature range.

1 *Battery module, consisting of twelve cells à 40 Ah. The liquid-based cooling via cooling plates allows the complete surface of the cells to be cooled. The procedure makes a very homogeneous temperature distribution feasible.*

2 *Opened battery system for electric vehicles with a capacity of 28 kWh. The rated voltage is 346 V. The modular concept allows simplified construction and easy repair of the battery system.*

The determined status data and measured values from the individual module-mounted electronics are analysed by a central battery management system. This determines the overall state of the battery, recognises defects, limits their effect and is responsible for communication on the vehicle bus system. Within the framework of model-based controls, models determine the maximum currents to enable faster control and better utilisation of the battery pack.

As pouch cells were used, which have aluminium and copper tabs as connectors, the connection technology presented a challenge. The connections between the cells need to be robust and long-lived, and cause as little loss as possible. Processes for conductive adhesion, ultrasonic welding and laser welding were developed and tested. Laser welding achieved very good results.

The "Fraunhofer Systems Research on Electromobility" was supported by the German Federal Ministry of Education and Research (BMBF).

DYNAMIC OPERATION OF A PV-POWERED REVERSE-OSMOSIS SYSTEM

In 2011, we extended our experience of photovoltaic systems technology by a field test of two reverse-osmosis systems on Cyprus. In the field test, the project consortium from Germany co-operated closely with the Cyprus Institute. The aim is to demonstrate dynamic system operation for desalination of seawater. To date, the reverse-osmosis processes have been operated in a stationary mode. Previously, large battery storage units were needed to support a purely photovoltaic power supply, without any grid connection. We developed operation management strategies and an innovative system design which mean that batteries will not be needed for this application in future.

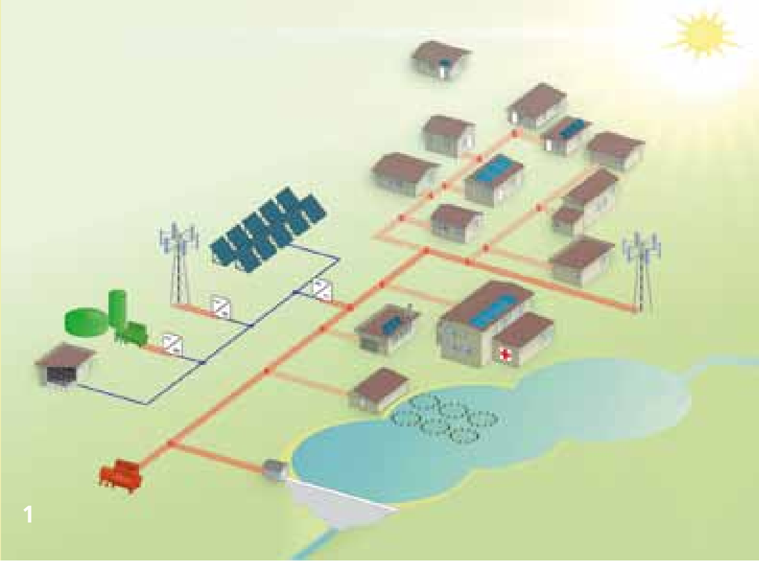
Julian Anhalt, Marcel Klemm, Sebastian Rauscher, Alexander Schies, Matthias Vetter, **Joachim Went**, Günther Ebert

1 *PV generator and two overseas containers, each housing a reverse-osmosis system for desalination of seawater. In the container to the left is a system for about 150 litres of desalinated water per day, and in the other container is a system for about 5 m³ per day. The location is the test field of the Cyprus Institute "Pentakomo Lab" on the Mediterranean coast.*

Up to now, the rapidly growing numbers of seawater desalination plants to provide water have not presented a sustainable model for the future, because the energy demand was met mainly by the consumption of fossil fuels. Solar power supplies and the construction of modern systems of different power categories located near the consumers must be promoted, so that seawater desalination, which is already indispensable for supplying water in many locations, can become part of a sustainable water supply. In particular, suitable energy recovery units have been lacking for small systems, which would enable dynamic and energy-efficient operation.

The team from Fraunhofer ISE has implemented two innovative system concepts with high energy efficiency in the systems installed on Cyprus. In each case, the system process can be operated dynamically and the power drawn is adapted to the currently available solar radiation. In addition to sophisticated process engineering components, this is achieved by a customised operation management strategy, which enables high efficiency values even in the partial load range and during start-up and shut-down processes. With this approach, photovoltaically powered desalination units can be implemented in future without the need for electricity storage units, improving their economic viability.

The project is supported by the German Federal Ministry of Economics and Technology (BMWi) within the "Inno-Net" programme and by our partners, Pairan Elektronik GmbH, IBC Solar AG, Gather Industrie GmbH, MAT Plasmatec GmbH, Katadyn Produkte AG and Technisches Büro Becker - TBB.



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SYSTEMS TECHNOLOGY FOR STAND-ALONE POWER SUPPLIES OF THE FUTURE

Most of the 1.44 thousand million people without access to electricity live in the sun belt of the earth with an inexhaustible potential of solar energy. With the price of solar generators falling continuously, photovoltaically powered stand-alone systems have become a better alternative to diesel generators. In order to meet more demanding specifications on efficiency, modularity and supply performance, Fraunhofer ISE is developing systems technology for the next generation of stand-alone power supplies. This includes the most modern power electronics, battery technology and system intelligence.

Nils Armbruster, Georg Bopp, Johannes Dréwniok, Michael Eberlin, Max Jung, Brisa Ortiz, Severin Philipp, **Florian Reiners**, Olivier Stalter, **Alexander Schies**, Simon Schwunk, Matthias Vetter, Jakob Wachtel, Günther Ebert

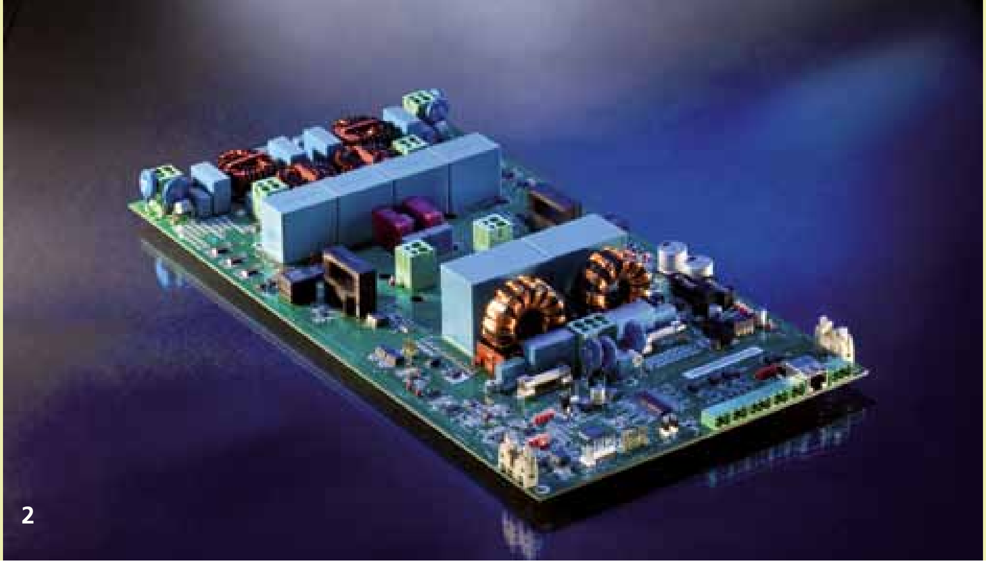
The stand-alone power supply solution is designed with a bi-directional stand-alone inverter, which is connected by a high-voltage bus to a hybrid battery system and a PV battery charger. The power electronics components reach efficiency values which have not been found previously in this application sector. A further innovation is the hybrid battery system, which combines the advantages of high cycling stability for the lithium-ion battery with the cost advantages of the lead-acid battery for the first time. The system is rounded out with an open communications protocol which connects all components to the central energy management system for system optimisation.

The bi-directional stand-alone inverter has a rated power of 120 kVA. Whereas conventional stand-alone inverters operate almost exclusively with a battery voltage of less than 60 V, it can be up to 1000 V in this application. This means that there is no need for transformers or step-up converters, which in combination with an innovative three-point topology leads to efficiency values exceeding 98 %. Normal stand-alone inverters are far from achieving this value. In order to maximise cost efficiency, power density and lifetime, the power electronics was implemented on the basis of a thick copper circuit board.

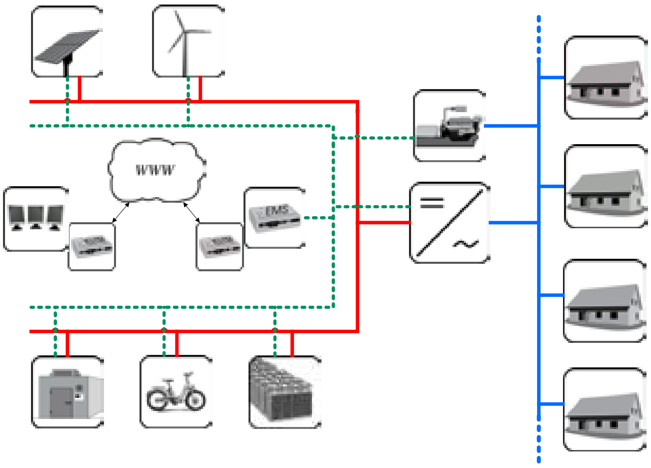
Battery systems still represent a large component of the life cycle costs of off-grid power supplies. By coupling a lead-acid battery with a lithium-ion battery, the aim is to lengthen the lifetime appreciably without the investment increasing too much due to expensive lithium-ion batteries. The lithium-ion battery is cycled frequently and is always used whenever there is charge in that battery. In summer, most of the cycles involve only this battery, while the lead-acid battery always remains in the completely charged state. In winter, complete charging occurs more frequently as a result. Simulations for a complete year of operation predict a capacity loss of 12 % for a solely lead-acid battery system compared to 4 % for a hybrid battery system.

The photovoltaic high-voltage battery charger has a rated power of 51 kW. With its six MPP trackers and a PV input

1 *The hybrid battery system and the PV system are connected via a high-voltage DC bus. In future, it should also be possible to integrate further electricity generators such as wind turbines and biomass systems. An inverter supplies three-phase AC electricity. A diesel generator can be integrated into the stand-alone system as an option.*



2 *Integrated circuit board for one of three identical modules in the photovoltaic high-voltage battery charger. Not only the power electronics but also all control electronics including the digital signal processor are located in this compact unit.*

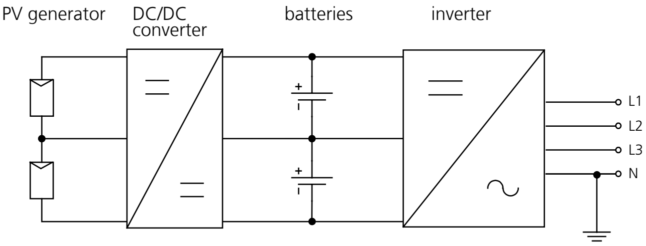


3 *Suitable communications infrastructure is needed to enable energy management with optimised operation management of auxiliary generators and intelligent load management. The communication cables for the CANopen protocol, which is independent of the power rails, are shown in green.*

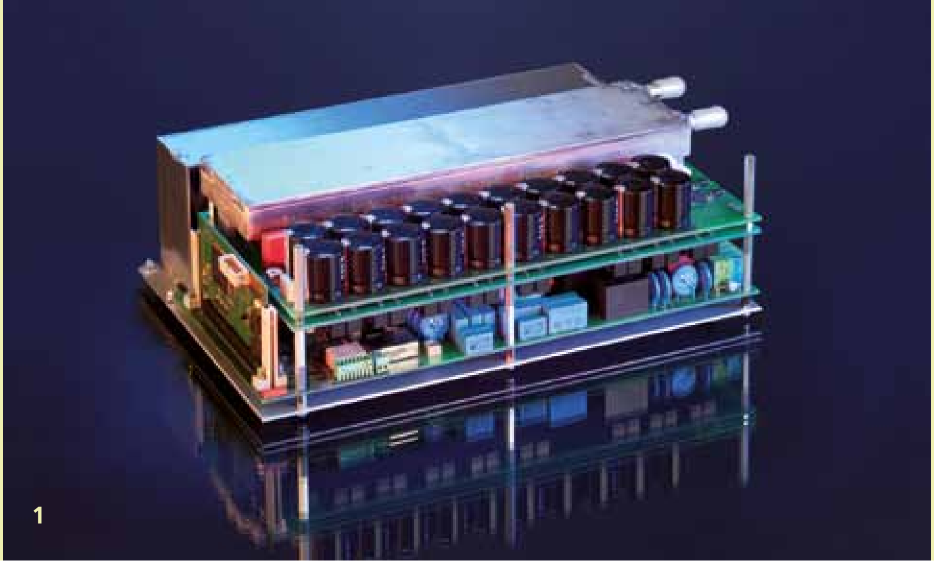
voltage range of 350 to 1200 V, it offers unprecedented lexibility for dimensioning the solar generator. In order to maximise the system efficiency, the newest generations of superjunction MOSFETs and silicon carbide diodes were used and transformers were avoided. Initial measurements confirmed promising efficiency values of more than 98.5 %. The high integration density of the power and logical components on a single circuit board also favour low production costs.

All system components communicate via the open CANopen protocol (application profile CiA 454 "Energy Management Systems") with the central energy management system. The energy management system is responsible for complete system optimisation. It ensures supply reliability also on days with low PV yields by connecting and disconnecting auxiliary generators and loads. Schedules for optimised operation of generators and switchable loads can be prepared on the basis of weather forecasts.

The "Innovative Photovoltaic Hybrid Systems Technology for Village Power Supplies (InnoSystem)" project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU). KACO new energy GmbH is our project partner.



4 *Block circuit diagram of the stand-alone system. An innovative step-up/step-down converter topology with a central earth offers great flexibility for dimensioning the solar generator and battery.*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HIGHLY EFFICIENT AND COMPACT CHARGER

The increasing number of battery-equipped electric vehicles will require a wide choice of charging equipment in future. The core component for charging the traction battery is a charger in the vehicle and a charging station for stationary charging. The charger connects the high-voltage traction battery of the vehicle to the electricity grid. Within the "Fraunhofer Systems Research on Electromobility", a transformerless, three-phase charger was developed with a high efficiency value and high power density.

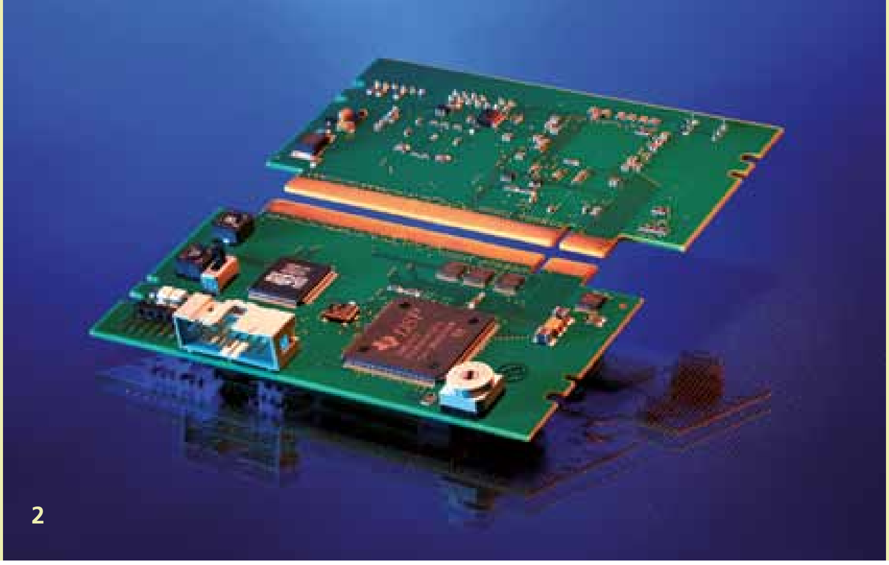
Bruno Burger, Benriah Goeldi, **Stefan Reichert**, Stefan Schönberger, Günther Ebert

Most currently available electric vehicle battery chargers only allow the battery to be charged with low charging power. Furthermore, these chargers are not able to provide any grid-supporting functions. At Fraunhofer ISE, we have thus focussed on developing a bi-directional charger, which can offer various system services. The charger can feed in or draw electricity to or from the grid with any arbitrary phase angle (cos φ) relative to the grid voltage. This enables it to offer system services, e.g. exchange of reactive power and provision of balancing energy and balancing power.

By removing the galvanic separation between the battery and the grid, the charger could be optimised with regard to power density and efficiency. Without the high-frequency transformer or any additional semiconductors and control electronics in the charger, its mass, losses and costs were reduced. A compact configuration for the power electronics was achieved by stacking the circuit boards, the semiconductor modules and the cooling components. The compact configuration of components required optimisation with the help of 3D visualisation. It allows active and passive electronic components and circuit boards to be matched to each other and positioned optimally to save space.

The application of power transistors based on new semiconductor materials such as silicon carbide (SiC) MOSFETs and JFETs has been discussed and researched for some time with regard to inverters for grid-connected photovoltaics. These new semiconductor materials have the advantage of low losses. Due to the low switching losses, the switching frequency of the charger can be increased without sacrificing efficiency.

SiC JFETs are integrated into the charger that was developed at Fraunhofer ISE. Due to the high switching frequency of



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80 kHz, the dimensions of the inductive components on both the grid and the battery sides could be drastically reduced. The charger with a hard switching, two-stage converter concept achieves a maximum efficiency of 97 % despite the high switching frequency. The efficiency value is almost independent of the voltage and power values. This is demonstrated by the fact that the efficiency value remains between 96 % and 97 % for the power range from 4 kW to 20 kW and over the entire battery voltage range from 300 V to 500 V.

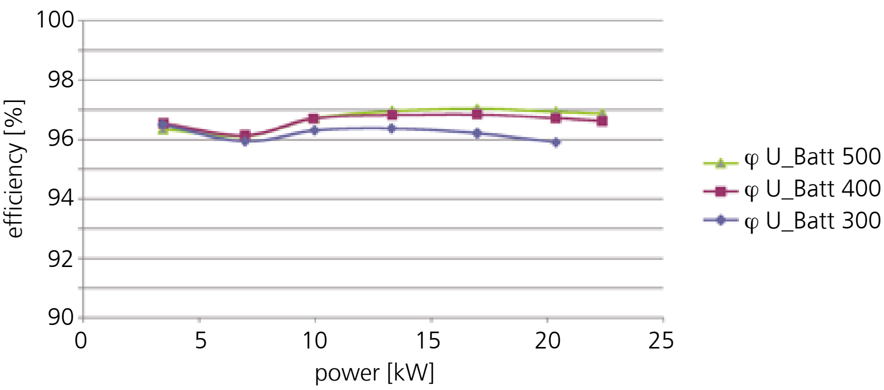
The high switching frequency presents a major challenge for the digital controllers. Therefore, a new controller board was developed specifically for the charger at Fraunhofer ISE. This is able to acquire high-resolution data on the currents and voltages with a sampling frequency of 80 kHz, run the controllers, and calculate pulse-width-modulated signals for switching the power transistors.

The charger operates bi-directionally. It is therefore able not only to draw electricity from the grid while charging but also to feed the electricity stored in the batteries back into the grid if required. This means that it can store electricity from fluctuating renewable sources like photovoltaics or wind turbines in the battery, and also support the grid at times when less electricity is generated from renewable sources. Electromobility thus offers the opportunity to make vehicle batteries accessible to the electricity grid for storage purposes. The large accumulated quantity of power connected via the bi-directional chargers, which makes it possible to compensate short-term power and frequency fluctuations in the electricity grid, is of particular interest.

The “Fraunhofer Systems Research on Electromobility” was supported by the German Federal Ministry of Education and Research (BMBF).

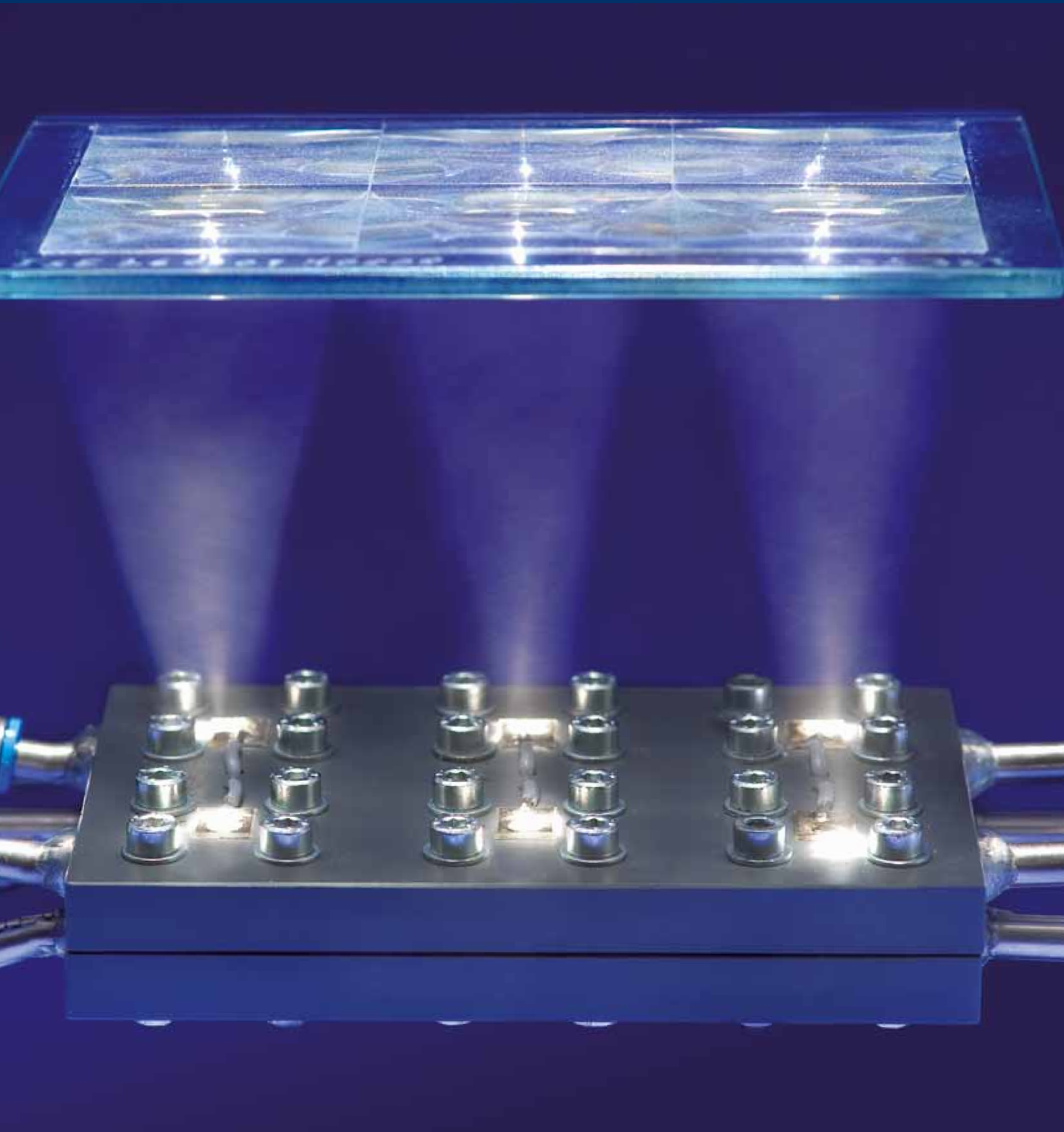
1 Bi-directional 22 kW charger. The high efficiency of 97 % and the high power density of 2.8 kW/l were achieved by using SiC semiconductors.

2 Circuit board with digital signal processor (DSP) for the control of power-electronic converters.



3 Efficiency versus power at different battery voltages for the three-phase, bi-directional charger.

ELECTRICITY FROM HYDROGEN



HYDROGEN TECHNOLOGY

Hydrogen releases usable energy in the form of electricity and heat when it reacts with oxygen in a fuel cell. As hydrogen is not found in its pure form in nature, it must be extracted from its diverse chemical compounds. This is achieved by applying energy. Ideally, hydrogen is produced by means of renewably generated electricity using electrolyser systems. A second approach is the reforming of gaseous or liquid fuels, so-called hydrocarbons or alcohols.

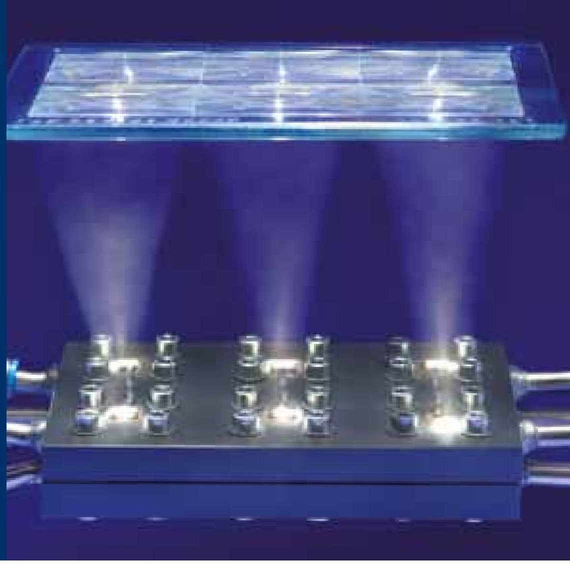
Although hydrogen is not a source of energy, as a universal fuel it will be an important component in the sustainable energy economy of the future. A long-term perspective is to store almost unlimited quantities of intermittently generated renewable energy as hydrogen, for example in underground caverns or the existing gas network. All desired energy services can then be provided with the accustomed reliability. The application potential of hydrogen is enormous: In distributed power supplies, fuel cells can supply heat and electricity from natural gas with a total efficiency value of up to 90 %. Fuel cells, combined with batteries, serve as non-polluting power sources for cars and buses. In addition, fuel cells in auxiliary power units (APU) provide the power for on-board electrical systems independently of the drive-train. Finally, miniature fuel cells can supplement rechargeable batteries in off-grid power supplies or small electronic appliances, due to the high energy density of hydrogen or alcohol.

Research on innovative technology to produce hydrogen and convert it efficiently to electricity and heat in fuel-cell systems is the core activity of the "Hydrogen Technology" business unit at Fraunhofer ISE. Together with our partners from science and industry, we develop components and the intermediate stages up to complete, integrated systems, mainly for off-grid, portable and mobile applications.

We develop reformer and pyrolysis systems to convert liquid hydrocarbons or alcohols into hydrogen-rich reformate gas. The systems consist of the actual reforming reactor and, depending on the type of fuel cell connected, gas treatment to raise the hydrogen concentration and reduce the amount of catalyst-damaging carbon monoxide and sulphur in the reformate gas. Such systems can be used in applications that include stationary combined heat and power plants (CHP), auxiliary power units (APU) and off-grid power supplies.

As our contribution to a sustainable energy supply, our portfolio also includes the conversion and usage of biomass. We have commissioned a technical prototype for gasification of wood, and now use it to demonstrate the feasibility of a new process which was developed by Fraunhofer ISE in co-operation with other partners. Furthermore, we are using pyrolysis processes to produce synthetic fuels from biomass and conventional combustible materials.

To obtain hydrogen from water, we develop membrane electrolysis systems supplying power from a few watts up to several kW, corresponding to the production of several hundred litres of hydrogen per hour. To gain deeper understanding of the processes occurring at the electrodes, we apply different characterisation methods such as scanning electron



HyCon(C) prototype for generating hydrogen directly from solar energy by water electrolysis. The module consists of III-V solar cells that are coupled to six PEM electrolysis cells. This enables hydrogen to be generated directly with a very high efficiency.

microscopy or cyclovoltammetry. At the beginning of 2012, we officially opened a public hydrogen filling station based on solar-generated hydrogen, to be used by fuel-cell bicycles, cars and buses.

The membrane fuel cell, operated with hydrogen or methanol, is our favoured energy converter in the power range from mW to five kW, being efficient, environmentally friendly, quiet and requiring little maintenance. We have equipped our Fuel Cell Test Centre to characterise this type of fuel cell. Furthermore, we cooperate with the VDE Testing and Certification Institute in providing advice on development and testing in compliance with existing standards and on the certification of fuel cells and systems.

In addition to the development of components and systems, we also work on the integration of fuel-cell systems into higher-order systems. We design and implement the electric infrastructure, including power conditioning and safety technology. In this way, we create the basis for commercially viable fuel-cell systems. We offer fuel-cell systems for auxiliary power units (APUs) in cars, trucks, ships or aeroplanes, as well as emergency power supplies and stand-alone power supplies for off-grid applications and portable electronic devices.

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CONSTRUCTION OF A 700 BAR HYDROGEN FILLING STATION BASED ON ELECTROLYSIS

To intensify its R&D on sustainable mobility and energy storage, the Energy Technology Division has constructed an innovative 700 bar hydrogen filling station on the premises of Fraunhofer ISE, with on-site hydrogen generation by electrolysis and electricity generated by a PV system. The filling station is accessible to the public and has provided environmentally friendly fuel for 700 bar hydrogen vehicles since March 2012. In addition to its primary function, the system offers diverse opportunities and platforms for further projects on hydrogen mobility, demand-side management and hydrogen injection into the natural gas network. The technically mature hardware allows practical experience and knowledge to be gained beyond the confines of the laboratory.

Ulf Groos, Tom Smolinka, **Christopher Voglstätter**, Christopher Hebling

While our energy supply is being re-oriented toward regenerative and climate-friendly sources, mobility still presents a problem which has not yet been solved definitively. Various approaches to CO_2-neutral mobility are currently being discussed among experts. Parallel to bio-fuels and purely battery-based electromobility, each with its own advantages and disadvantages, electromobility based on hydrogen from renewable sources and fuel cells is also one of the solutions under discussion.

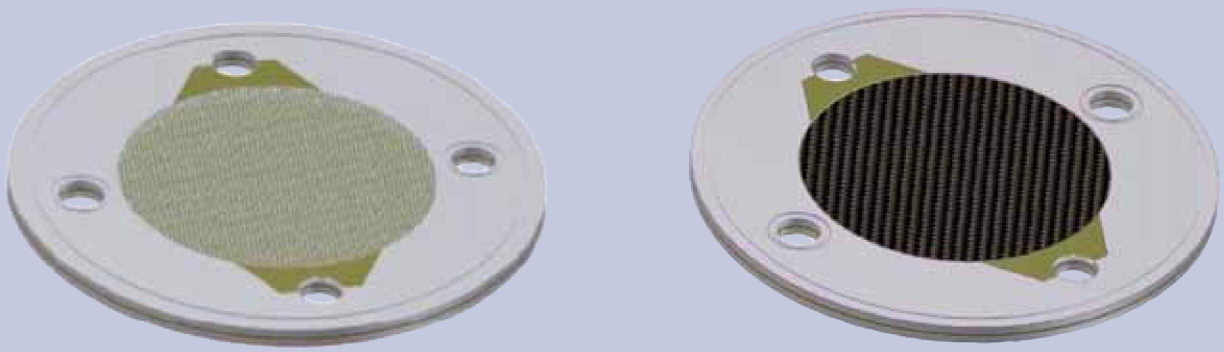
In contrast to the other approaches, hydrogen mobility suffers from the lack of infrastructure: a classic chicken and egg problem. Various initiatives from the public and private sector have the goal of establishing a nation-wide hydrogen infrastructure in Germany by the roll-out of the first pilot series of hydrogen vehicles in 2014. Construction of a hydrogen filling station in Freiburg means that a vertex in the filling station infrastructure will be serviced and a corridor into Switzerland and France will be provided.

1 *Filling the tank of a hydrogen-fuelled vehicle with hydrogen.*

The filling station, which has been publicly accessible since March 2012, features 350/700 bar technology and on-site hydrogen production by a state-of-the-art PEM electrolyser. The required electricity will be obtained with the highest possible solar fraction from a dedicated PV system on site, with the remainder being certified electricity from renewable sources.

In addition to providing hydrogen for cars, the filling station will also serve as a basis for diverse research topics relevant to mobility and energy storage. Thus, in designing the system, the pre-conditions were created for the system to operate experimentally in a smart grid and act as a research platform for further projects in the areas of hydrogen mobility, hydrogen-fuelled low-power traction and hydrogen injection into the natural gas network. The technically mature hardware will allow practical experience and knowledge to be gained beyond the confines of the laboratory.

The project was supported by the Baden-Württemberg Ministry for the Environment, Climate and Energy Economics with funds from the State Infrastructure Programme and by the National Innovation Programme (NIP) for Hydrogen and Fuel-Cell Technology by NOW GmbH (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie).



1

NEW HIGH-PRESSURE ELECTROLYSIS STACK FOR EFFICIENT H_2 PRODUCTION

Hydrogen will be used in future as a multi-facetted and storable fuel for a broad spectrum of applications. Polymer-electrolyte-membrane (PEM) electrolysers are particularly suitable for efficient production of hydrogen in combination with renewable energy sources. In a project funded by the European Union (EU), we are currently developing a cost-effective, high-pressure stack for PEM electrolysis. The novel stack consists mainly of technically innovative components that are suitable for mass production, e.g. new electrodes, a new cell frame construction and cast gaskets. The stack should have an efficiency value of at least 75 % (LHV – lower heating value) and a lifetime of more than 40 000 hours.

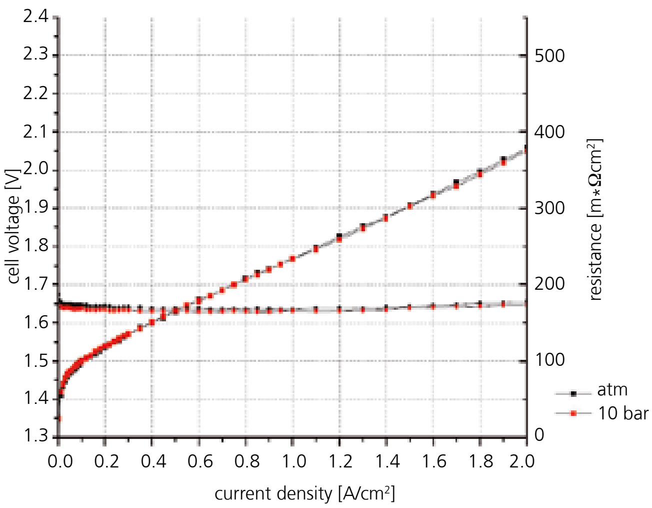
Beatrice Hacker, **Emile Tabu Ojong**, Sebastian Rau, Tom Smolinka, Christopher Hebling

PEM electrolysers represent an excellent method to produce hydrogen efficiently and flexibly, both for mobile and stationary applications. However, despite recent progress in PEM technology, there are still challenges to be overcome for commercialisation, e.g. high material and system costs, inadequate lifetime and expensive production methods.

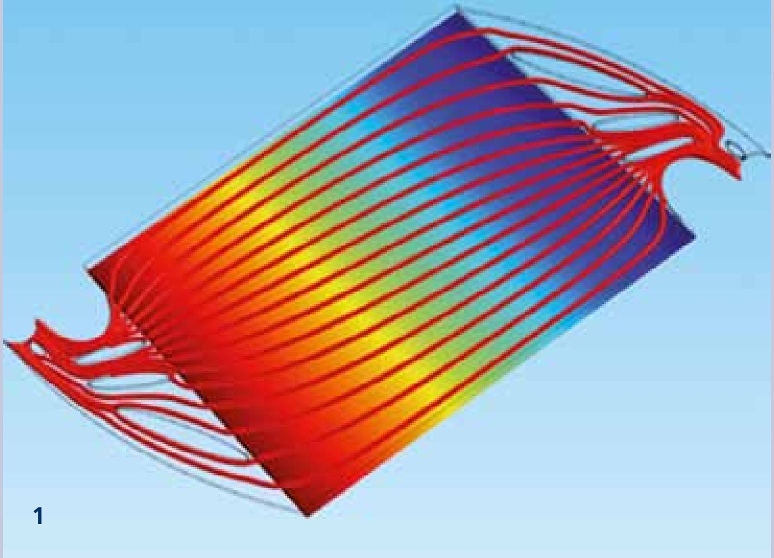
Together with European partners from research institutions and industry, we are addressing these issues in the EU-funded "NEXPEL" project by targeted further development of materials and components for application in high-pressure electrolysers.

A new stack design is being developed to improve the conventional concept. In order to reduce production costs, flow fields are not machined into the bipolar plates (Fig. 1). Based on cost models and experiments on the corrosion behaviour of bipolar plates and current distributors, we have chosen suitable materials for the cell construction. A two-phase flow model was used to optimise the current distributor. Furthermore, a special protective coating will minimise hydrogen embrittlement of the cathode. In order to optimise the sealing of the high-pressure system (50 bar), the conventional pocket concept for the bipolar plate was replaced by a cell frame of inexpensive polymer with an attached cast gasket, which provides both the sealing and the inlets and outlets for all fluid fluxes.

1 *Concept of the new stack design, which is currently being investigated in short stacks at Fraunhofer ISE. The half-cell for the oxygen side can be seen to the left and for the hydrogen side to the right.*



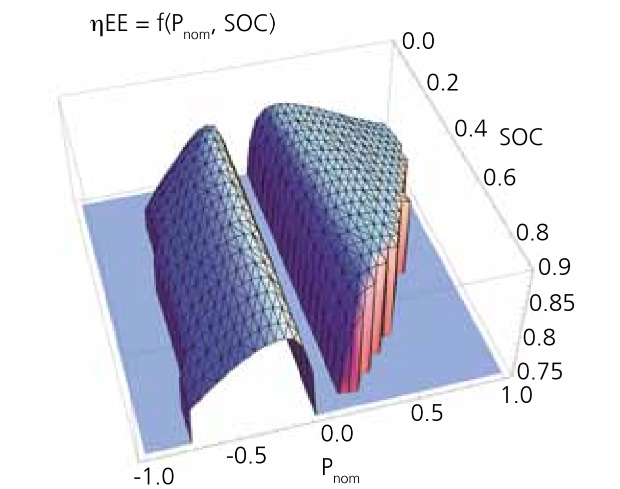
2 *Typical performance data for the preferred material combination, measured in a 25 cm² laboratory cell at 80 °C and 10 bar.*



SIMULATION-SUPPORTED DESIGN OF REDOX-FLOW BATTERIES

To develop a scalable storage unit for electricity with an electric power of 100 kW_{el} and a capacity of 1 MWh_{el}, we at Fraunhofer ISE are addressing stack and system development and battery management for redox-flow batteries. We use simulation-supported analysis and design of redox-flow batteries to identify optimisation potential at the cell and stack level and then apply this when developing the design further. Within the project entitled "1 MWh redox-flow grid-connected storage units", we are developing optimised cell stacks with power ratings of 1, 5 and 35 kW_{el} for application in stand-alone systems or also grid-connected storage systems. Cycling efficiency values of more than 80 % can be achieved at the cell level.

Kolja Bromberger, Martin Dennemoser, Tom Smolinka, Matthias Vetter, Christopher Hebling



2 *Energy efficiency (EE) for the charging/discharging processes as a function of the state of charge (SOC) and the normalised power (P_{norm}).*

1 *Stationary fluid dynamic simulation of a geometrical design for a half-cell showing the pressure field and flow lines.*

Redox-flow batteries store electricity as chemical energy in the active mass of liquid electrolytes, which are stored in separate tanks for the positive and negative sides. For energy conversion, the electrolytes are pumped through the electrochemical cell, so that the active ions of the electrolyte can be charged or discharged. The central component of a redox-flow battery is thus the cell stack as an electrochemical conversion unit.

With CFD simulation, fundamental fluid-technological questions are answered concerning the design of the inlet and outlet zones at the cell level, liquid management within the stack and geometrical relationships. Using the 1 kW cell design as an example, Figure 1 shows the flow patterns of the electrolyte through a half-cell and the pressure loss across an electrode material.

To reduce the storage costs, designs are developed for cells which can be produced in large numbers by injection-moulding processes. We optimise the electrical operating performance of the conversion unit by screening materials for the electrodes, membranes and bipolar plates. A test platform to determine system-relevant parameters is available for characterisation and evaluation purposes.

Drawing on these measurements, in parallel we develop model-based control strategies, which allow energy-optimised operation of the redox-flow battery system. So-called "smart redox flow control" allows an optimised mode of operation by minimising energy losses in the peripheral devices and well-matched integration into the higher-order energy system, which lengthens its lifetime.

AMES-POWER: PORTABLE FUEL CELL SYSTEM

Together with our project partners, DMTpe AG, bebro electronic GmbH, Freudenberg FCCT KG, Chemetall GmbH and TU Bergakademie Freiberg, we have developed a fuel cell system capable of cold starting as a charging station for use in emergency medicine. The application of a novel chemical hydride as the energy source is a special feature. Alternatively, other hydrogen storage units can be connected. The fuel cell system was dimensioned for an output power of 100 W_{el} and designed for operation under ambient temperatures from -15 °C to +50 °C. In designing the system, compliance with standards and the potential for series production were primary considerations.

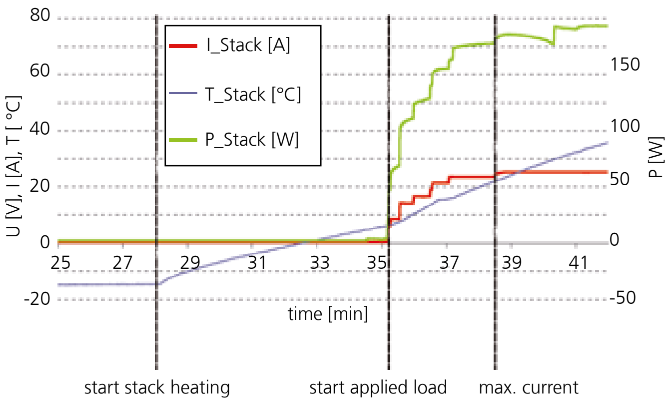
Gerrit Ammon, Kolja Bromberger, Ulf Groos, Stefan Keller, **Wolfgang Koch**, Johannes Kostka, Christian Sadeler, Christopher Hebling

In the fuel cell system developed here, the hydrogen is produced by the environmentally friendly reaction of sodium boron hydride tablets with formic acid. The hydrogen required by the fuel cell is produced on demand in the hydrogen generator. Alternatively, a pressurised gas cylinder or a metal hydride storage capsule can be connected.

The central control unit was designed in collaboration with bebro electronic GmbH as a universal control unit which can be used as a basis for further applications. Two independent processors are installed to ensure backup in the monitoring and control of safety-relevant actuators and sensors. An integrated high-performance recyclable battery serves as a power buffer between the fuel cell and the connected load.

We developed the fuel cell with the aim of optimising its production. The typically expensive bipolar plates were replaced by a novel concept employing films. The fuel cell is air-cooled.

1 *AMES, a portable fuel cell system capable of cold starts.*



2 *Power characteristic of the AMES fuel cell system during the start-up period, for an outdoor temperature of -15 °C.*

The heat which is generated in the cell is transferred horizontally via cooling plates out of the fuel cell and is removed from the entire system by a fan. With this innovative stack concept, we achieve unusually homogeneous performance of all cells.

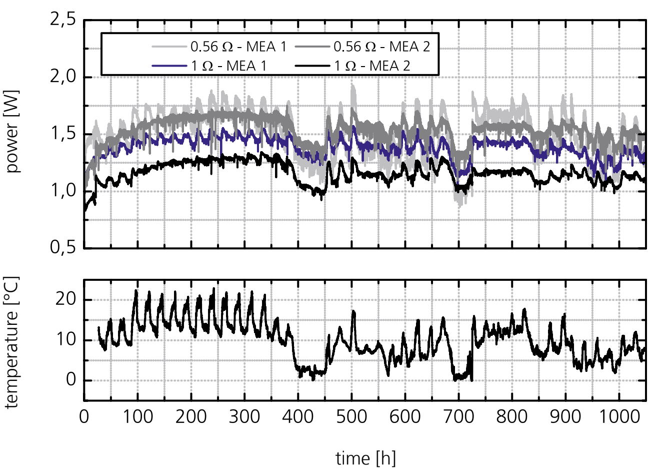
The E-PAC® housing concept from DMTpe keeps all components in the correct position and protects them against mechanical shock. Cooling channels and openings can be easily integrated into the housing.

The project was supported by the German Federal Ministry of Education and Research (BMBF).

STATISTICAL INVESTIGATION OF PEM FUEL CELL LIFETIME

We developed a test stand suitable for outdoor use to investigate the lifetime and performance characteristics of fuel cells. Fuel cell components such as membrane-electrode assemblies and gas diffusion layers can be characterised in it under real conditions, e.g. in the presence of atmospheric pollutants. The test stand analyses 30 test cells simultaneously to ensure high reproducibility. In combination with a gas cylinder cabinet, the test stand can be set up at any location and operated completely autonomously due to the integrated controls and safety monitoring.

Gerrit Ammon, Anneke Georg, Dietmar Gerteisen, Peter Gesikiewicz, Ulf Groos, Timo Kurz, **Christian Sadeler**, Mario Zedda, Christopher Hebling



2 Time-averaged power and temperature profiles of four module groups equipped with different MEAs and operating at different operation points.

1 Test stand for fuel cell characterisation and gas cylinder cabinet on the mountain of Schauinsland near Freiburg. The units are designed for outdoor use.

For statistical investigation of degradation effects or other factors of influence, e.g. atmospheric pollution, it is necessary to characterise many cells so that possible effects due to material or production defects can be eliminated. To this purpose, we have developed a test stand at Fraunhofer ISE, with which we can characterise the performance of up to 30 cells simultaneously. In addition to other types of technology, we can investigate cost-effective test fuel cells manufactured by injection moulding, which were developed together with the FWB Kunststofftechnik company. The test stand is designed such that the cells can be investigated under different loads. Selected cell temperatures, the ambient temperature and humidity are also measured in parallel to operating parameters such as cell voltage and cell current. A heating element integrated into the test stand means that it can also be operated at outdoor temperatures below freezing point.

We are currently operating four test stands in Freiburg with different levels of background urban or industrial air pollution and in a location with good air quality to investigate the effect of air pollution and its dependence on the operating point and the choice of membrane-electrode assembly. For ex situ analysis, we apply ICP-MS (Inductively Coupled Plasma Mass Spectrometry) to identify impurities in the product water. By analysing the peripheral components used in parallel, the source of the contamination can be traced back to the peripheral components, material impurity or atmospheric pollution.

The work was supported by the German Federal Ministry of Education and Research (BMBF).

HYDROGEN AND FUELS FROM BIOGENIC WASTE

Energy from biomass is particularly climate-friendly if biogenic waste is used. This often has a high water content which prevents its use in many conversion processes. However, aqueous phase reforming is able to use these materials, as elevated process pressure combined with moderate temperatures prevents the water from evaporating. At Fraunhofer ISE, we have developed catalysts for aqueous phase reforming and integrated these into a continuous process which allows hydrogen or alkanes, depending on the process conditions, to be gained from a great variety of biogenic substances.

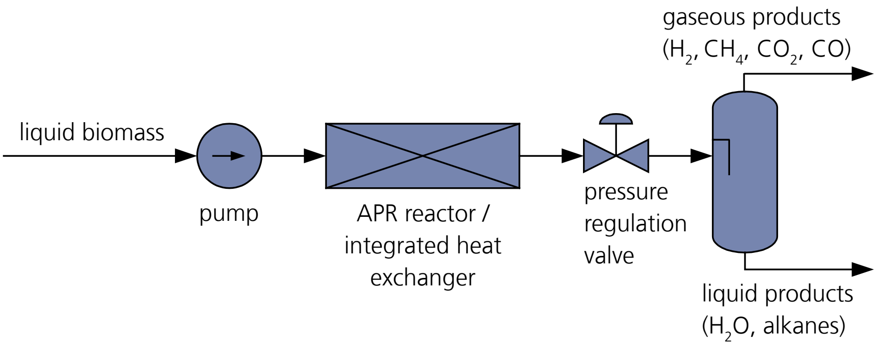
Thomas Aicher, Raphael Marro, Alexander Susdorf, **Achim Schaadt**, Malte Schlüter, Daniela Villacreses, Christopher Hebling

Biogenic waste from agriculture or forestry either has not been used at all or has been converted very inefficiently up to now. Its worldwide energy potential is estimated to be about 50 EJ, which corresponds to app. 12 % of the global primary energy consumption.

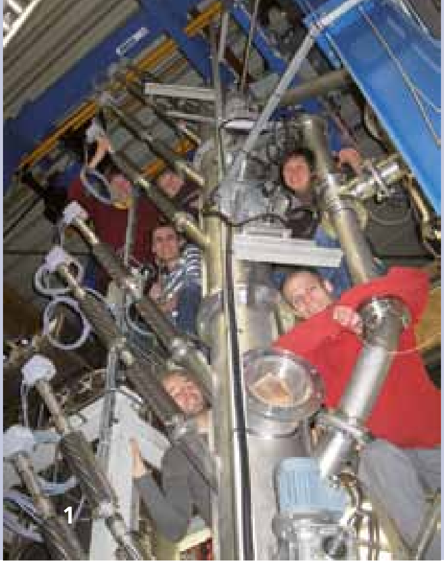
Aqueous Phase Reforming (APR) could serve to convert a large proportion of this inexpensive biomass into fuels such as hydrogen and alkanes, which could be used e.g. as motor fuels. The pre-condition is that the biomass already exists in the liquid state or it can be liquefied by one of the well-known preliminary treatment procedures such as flash pyrolysis. We initially applied the APR process, which can convert a broad spectrum of raw materials, to substances which can be easily produced from biomass, e.g. bio-ethanol and glycerine.

The chemical engineering process is very simple. Initially, the liquid is compressed to a pressure of 30–50 bar. As liquids are not very compressible, little energy is needed for this process. Before it enters the reactor, the liquid is heated to about 250 °C; the temperature is kept below the evaporation temperature in all cases. For the APR process, we have developed both a scalable reactor and a stable catalyst. Depending on the choice of catalyst, we generated either mainly hydrogen or mainly alkanes. As the product gases are already present at an elevated pressure level, the energy demand for the compression which usually follows is reduced significantly.

1 *APR reactor with temperature sensors mounted along the side, during insertion into the thermal oil container which ensures homogeneous heating.*



2 *The pump compresses the liquid biomass in the APR reactor to the necessary pressure, which is regulated by the process control valve. Subsequently, the fuels can be separated and purified for the intended application.*



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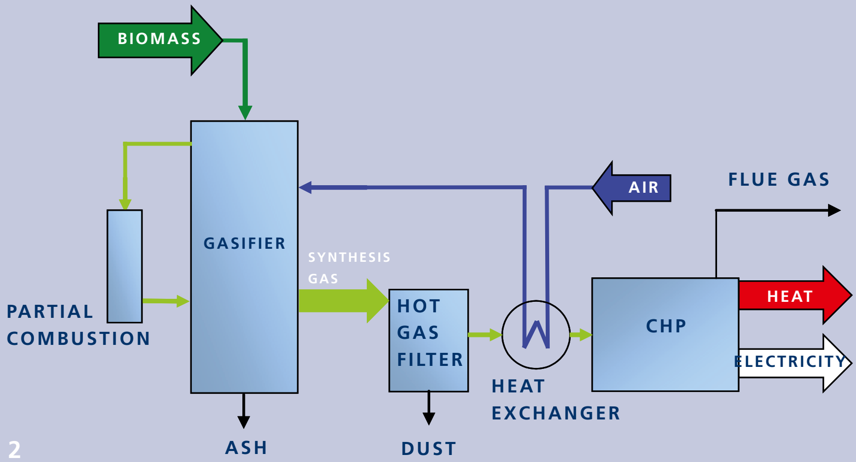


2

BioSyn BIOMASS GASIFIER PRODUCES TAR-FREE SYNTHESIS GAS

In the Division for Energy Technology, the technological implementation of an innovative process for biomass gasification was demonstrated with a multiple-stage, fixed-bed gasifier for 50 kW fuel heating power. The aim of the process is to produce tar-free synthesis gas from different types of biomass, e.g. wood pellets and bio-coal. The synthesis gas can then be converted to electricity and heat by co-generation. Innovative features include the movable gratings to separate the individual reactor stages, the transport of smouldering gas without valves by variation of the filling heights in the different stages and the external partial combustion of smouldering gas, which makes auto-catalytic cracking of the undesired tars feasible.

Thomas Aicher, Luisa Burhenne, Christian Lintner,
Lisbeth Rochlitz, Christopher Hebling

Biomass gasification is an environmentally friendly technology to produce synthesis gas from regenerative sources. It offers the opportunity to subsequently generate electricity and heat by co-generation with high efficiency on demand. By using regional resources, gaining energy from biomass strengthens the local value chain and guarantees closed material cycles. In regions remote from the grid, this technology presents a good alternative to expensive and lossy extension of the grid or a diesel generator. To date, there are not any systems in the power range < 1 MW, which could be operated successfully according to economic and technological criteria, and provide long-term experience on fully automatic operation in the co-generation mode. This is mainly because many tars are formed during the decomposition of wood, which impair the functionality of subsequent components, particularly heat exchangers and motors.

1 *BioSyn gasifier under construction, not yet insulated.*

2 *Simplified schematic diagram of the patented BioSyn gasification process: a hot gas filter is used as the only gas cleaning stage before conversion of the synthesis gas to electricity and heat in the combined heat and power (CHP) plant.*

At Fraunhofer ISE, an innovative process was developed, so-called BioSyn gasification, which can be applied to many different types of biogas and is protected by patent. The process produces tar-free synthesis gas. This is achieved by special gas transport which occurs without valves by variation of the filling height in the different stages, and strict separation of the individual process steps. Apart from a hot gas filter, no further gas purification is needed for usage in a gas-fuelled motor. Depending on the specifications for the heating value of the synthesis gas, it should be possible to operate the gasifier with different raw materials, so that it is flexible with regard to location. The operating principle of the internal cracking of tars was proven in laboratory experiments at Fraunhofer ISE. The theoretical cold gas efficiency value for the process (= chemical energy in the product gas / chemical energy in the fuel) is greater than 80 %. This is a clear increase compared to existing systems.

Due to its simple technical components, which have already been tested for long-term durability, the BioSyn gasifier requires little maintenance and operation is economically viable also for low power (app. 150 kW fuel power).

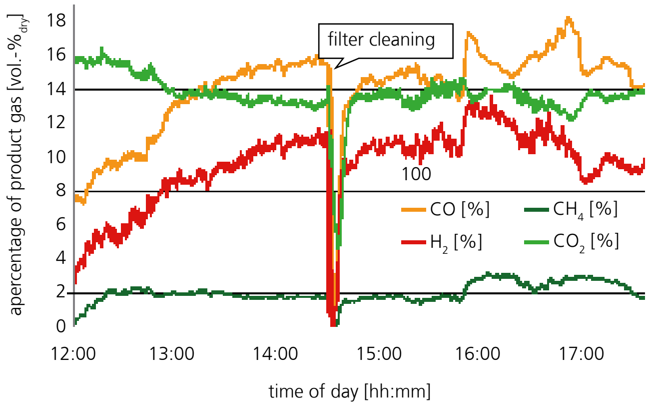
In addition to diverse laboratory experiments, the process was demonstrated by constructing the multiple-stage BioSyn fixed-bed gasifier in a technological pilot scale (for app. 12 kg biomass per hour, corresponding to 60 kW for wood),

3 *Various types of biomass feedstock for gasification (from left to right): bio-coal, wood pellets, bark pellets.*

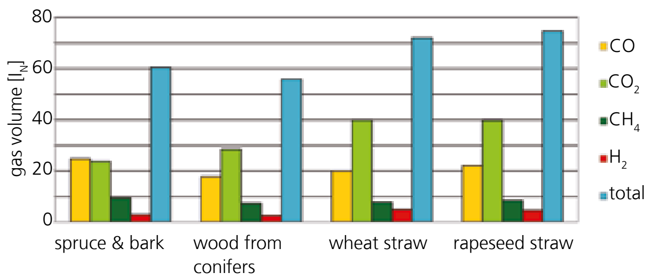
commissioning and testing and optimising it with wood pellets and bio-coal. In laboratory experiments, we investigated the gassing behaviour and product gas composition of different types of biomass, including woodchips of beech, spruce, pine and poplar with different water content, pellets of conifer wood, with and without bark, wheat straw, rapeseed straw, fermentation residues and bio-coal. It was observed that a high water content and a high proportion of cellulose result in more rapid conversion to synthesis gas than a high lignin content as in wood. Correspondingly, shorter residence times in the reactor should be chosen for grass-type biomass with a high cellulose content than for woody biomass with a high lignin content. Parallel to the experimental investigations, the individual process steps of the thermochemical conversion were simulated with Matlab/Simulink for various types of biomass. The goal is to be able to predict the process even when the operating parameters are varied. In addition, this serves to determine an optimal control strategy for automating the system.

By optimising the necessary peripheral components (input and output transport) and the system controls, valuable knowledge was gained on the gasification of wood pellets and other solid forms of biomass to produce tar-free synthesis gas. The technological pilot system at Fraunhofer ISE is available for other investigations. This offers interested companies the possibility to take a leading position worldwide.

The project was supported as part of the Climate Initiative by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).

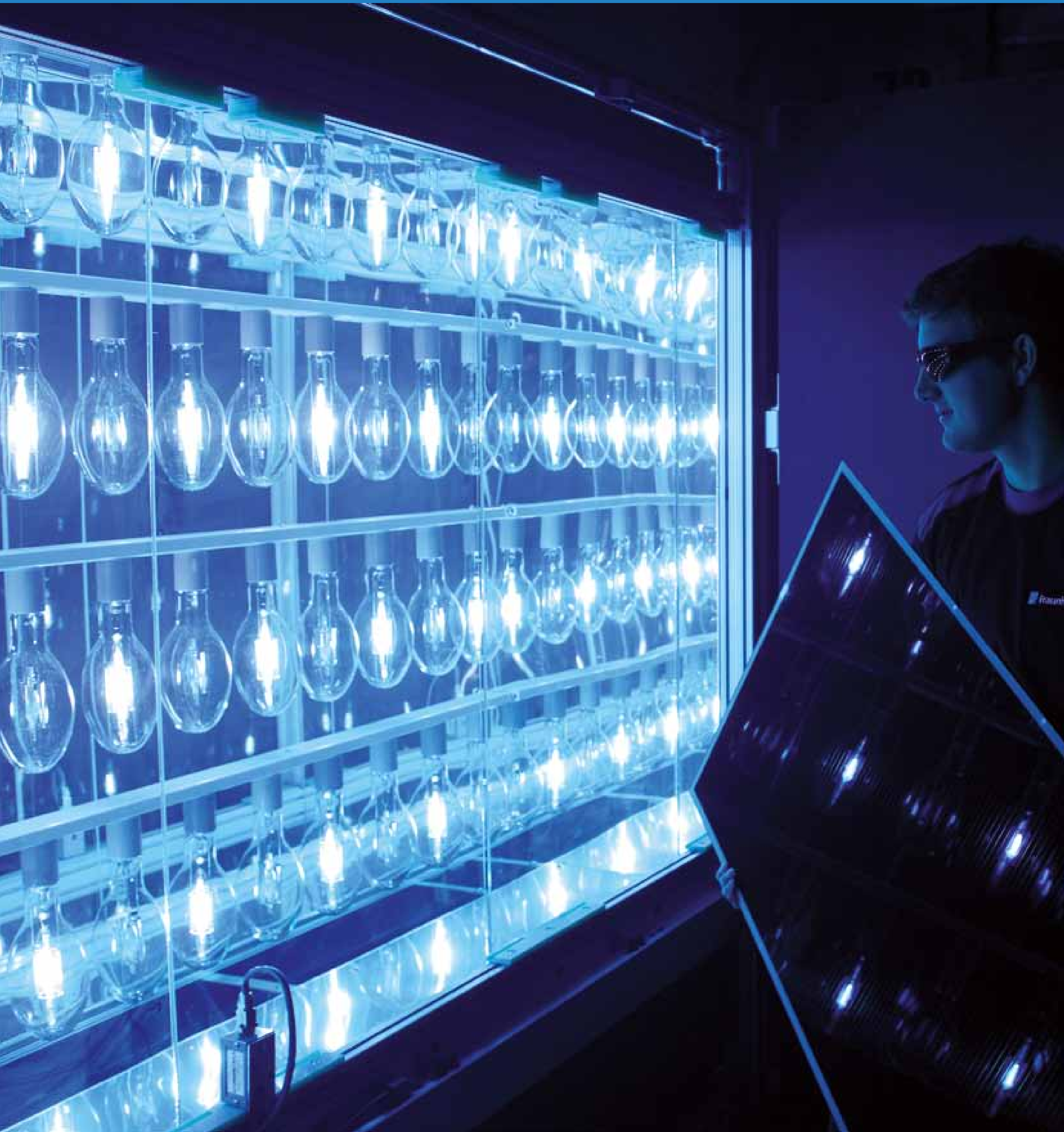


4 *Dry product gas composition from technical scale gasifier test with wood pellets at up to 60 kW biomass feed (lower heating value). The test started shortly before 12:00. Drastic changes in composition, as seen for example at 15:50, 16:20 and 17:00, result from varying the process parameters, i.e. the amount and location of air feed and the biomass residence time in the reactor stages. The goal for optimisation is to reach a product gas with high calorific value and low methane content.*



5 *Product gas amounts in litres (CO, CO_2, CH_4 and H_2) from laboratory pyrolysis experiments with four different biomass samples under the same process conditions. The experiments were conducted with 700 °C hot nitrogen flowing through a fixed bed of biomass. Due to its high cellulose and mineral content, straw produces more gas than wood with its high lignin content.*

QUALITY CONVINCES



SERVICE UNITS

In the booming solar industry, the role of materials testing, certification and quality control is becoming increasingly important. As a complement to our research and development work, we offer related testing and certification services to clients. At present, Fraunhofer ISE has four accredited testing laboratories: TestLab Solar Thermal Systems, TestLab Solar Façades, TestLab PV Modules and the PV calibration laboratory with CalLab PV Cells and CalLab PV Modules. Our further service units include a battery test laboratory, an inverter laboratory, a lighting laboratory, a test capacity for heat pumps and evaporators, a laboratory for quality control and characterisation of phase change materials (PCM), a test laboratory for adsorbent and TestLab Fuel Cells.

Beyond the service aspect, these units also have a research function. The insights gained during characterisation, certification or testing can become the kernel for new research topics, be it in product development or improvement, further development of testing methods and standards, or theoretical development, e.g. in model-based prediction of aging.

TestLab Solar Thermal Systems has been accredited according to DIN EN ISO/IEC 17025 since May 2005. The testing facilities include:

- test stand for solar air-heating collector testing
- hail test stand
- system and heat storage test stand
- outdoor test stand with trackers and a dynamic rack
- indoor test stand with a solar simulator (max. aperture area 3 x 3.5 m^2)
- collector test stand up to 200 °C

The main work of TestLab Solar Thermal Systems is based on commissions from the industry to test collectors according to European collector standards or quality labels such as the "Solar Keymark Scheme Rules" of CEN. A special feature is the possibility to test collectors at temperatures up to 200 °C. This makes it feasible to test new applications such as process-heat generation and to conduct stagnation tests, (see page 137).

TestLab Solar Façades was accredited according to DIN EN ISO/IEC 17025 in 2006. It offers a comprehensive range of characterisation for innovative building components and materials to developers and planners of façades, windows and façade components, including shading devices. In particular, the range of services encompasses the characterisation of components which also serve as active solar energy converters (e.g. transparent façade collectors and BIPV). In addition to accredited tests, comprehensive services concerning glare protection and daylighting are offered, (see page 138).

Testing of the following properties is included in the accreditation:

- g value (also calorimetric measurement)
- transmittance: spectral and broadband
- reflectance: spectral and broadband
- U value

In 2011, TestLab PV Modules was granted extended new accreditation for the type authorisation of PV modules according to IEC 61215 and IEC 61646 as well as accreditation for the first time concerning the safety standard, IEC 61730. This meant that the testing sequences could be further optimised and the time to test PV modules for type approval has been reduced yet again. The goal of the facility is quality control of PV module reliability, which is becoming an increasingly important issue in the continually growing market. Within the framework of its co-operation with the VDE Institute, Fraunhofer ISE is responsible for all performance tests, while the VDE Institute issues certificates after successful testing. In addition to the tests for product type approval, tests are also carried out to accompany the development of PV modules and module components according to the manufacturers' specifications. TestLab PV Modules cooperates closely with the PV calibration laboratory at Fraunhofer ISE, comprising CalLab PV Cells and CalLab PV Modules, (see page136).

The fourth accredited laboratory, having gained this status in November 2006, is our calibration laboratory with CalLab PV Cells and CalLab PV Modules, which is one of the international leaders in this field. The calibration of photovoltaic modules plays an important role in product comparisons and for quality assurance of PV power plants. The cell calibration in CalLab PV Cells, which has been accredited as a calibration laboratory with the Deutscher Kalibrierdienst (DKD – German Calibration Service) since the end of 2008, serves as a reference for industry and research (see page. 134). The module calibration in CalLab PV Modules is part of the module certification process, on the one hand. On the other hand, it serves to control the quality of systems and to support development, (see page 135).

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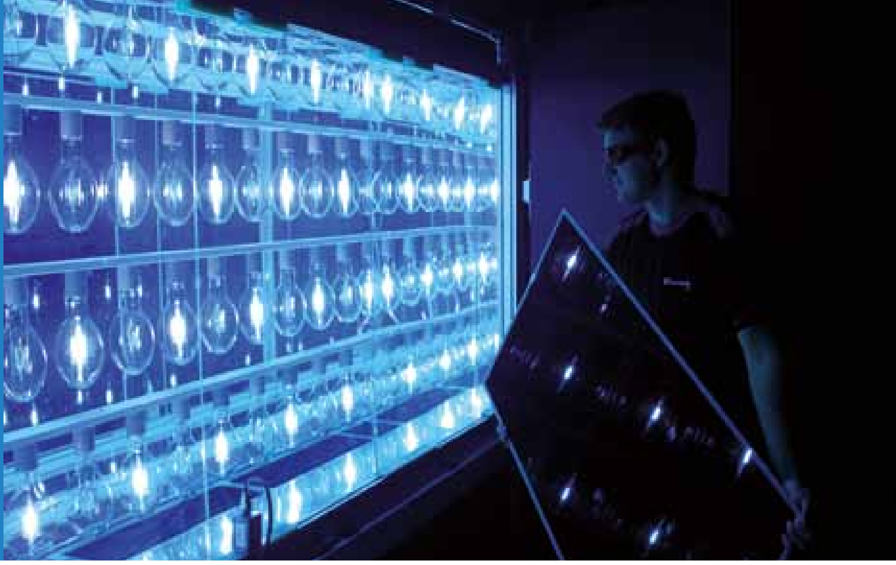

Facility for calibration of photovoltaic modules: Recently developed solar simulator and light-soaking units are used to prepare modules optimally for the calibration process. The services offered by Fraunhofer ISE contribute to quality assurance for solar technology. They also serve a research function. The insights gained during characterisation, testing or authorisation can be incorporated into new research topics – be it in product development or optimisation, in the further development of test methods and standards or in theoretical development, e.g. of model-based aging prediction.

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TestLab Fuel Cells	Ulf Groos	Phone +49 761 4588-5202 ulf.groos@ise.fraunhofer.de

CALIBRATION OF SOLAR CELLS ACCORDING TO INTERNATIONAL STANDARDS

CalLab PV Cells at Fraunhofer ISE offers the measurement and calibration of solar cells from a wide range of PV technology and works with companies and institutes at national and international levels to develop accurate measurement methods for new types of technology. CalLab PV Cells is one of the internationally leading photovoltaic calibration laboratories. The calibration laboratory serves as a reference for research and industry. Solar cell manufacturers commission us to calibrate their reference solar cells for production lines according to international standards.

Tobias Gandy, Jochen Hohl-Ebinger, Thomas Hultzsch, Robert Köhn, Katinka Kordelos, Markus Mundus, Simone Petermann, Michael Schachtner, Wendy Schneider, Holger Seifert, Astrid Semeraro, Karin Siebert, **Gerald Siefer, Wilhelm Warta**, Jan Weiß, Jutta Zielonka

CalLab PV Cells is accredited according to ISO/IEC 17025 as a calibration laboratory for solar cell calibration with the Deutscher Kalibrierdienst (DKD). With the support of the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU), and in co-operation with PV manufacturers, we work continuously on improving tolerances and developing new measurement procedures. For example, the change in solar cell parameters at higher temperatures (as characterised by their temperature coefficients) plays a decisive role for their yield in practical application. A new procedure, with which temperature coefficients can be determined with a previously unattainable accuracy, has proven to be very attractive for manufacturers of solar cells. The special feature of our method is measurement of the temperature-dependent spectral response.

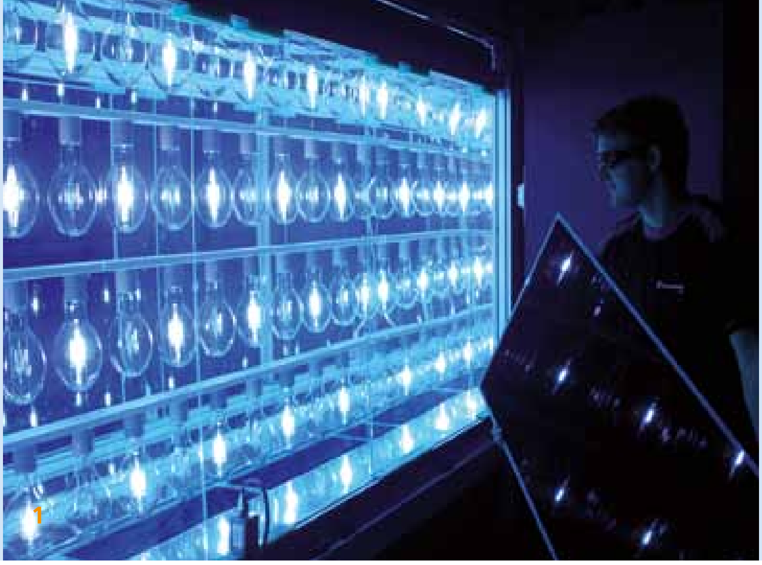
After our move into new laboratories, we were able to optimise our measurement facilities with regard to the ambient conditions. This, combined with improved infrastructure, means that we can supply the industry even better than previously with references.

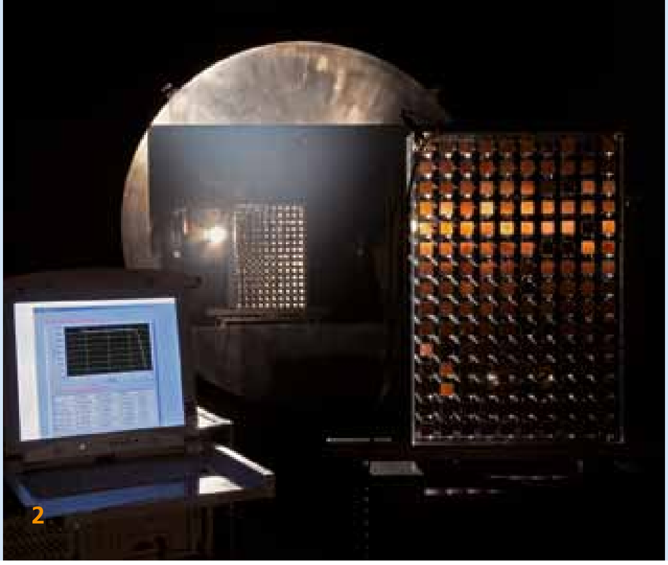
1 *The spectral response is also measured for large-area solar cells with high accuracy and exact specification of the measurement uncertainty.*

In order to guarantee the comparability of measurements for solar cells from different types of PV technology, increased efforts are being made to develop measurement procedures for novel solar cells. The focus is on thin-film and organic solar cells. Multi-junction cell structures present a particular challenge. Here, we have taken advantage of our experience with the calibration of multi-junction solar cells for space and terrestrial concentrator applications. By extending our facilities for calibrating multi-junction cells of thin-film materials, we were able to support the rapid development of this technology even better this year with accurate measurements.

Calibration of multi-junction solar cells

- The spectral response or the external quantum efficiency of multi-junction solar cells is measured using our grating monochromator set-up that was specifically extended for the measurement of multi-junction solar cells.
- We measure the current/voltage characteristics with our multi-source simulator under almost any standard conditions, such as AM0 (ISO 15387) for space applications and AM1.5d (ASTM G173-03) for concentrator applications.
- Concentrator cells can be measured with our flash lamp simulator at concentration ratios of up to 5000.
- In addition, we have taken a solar simulator with six independent light sources into operation for calibrated measurement of solar cells with up to six pn junctions.





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2

CALIBRATION OF PV AND CONCENTRATOR MODULES

CalLab PV Modules at Fraunhofer ISE has been one of the internationally leading photovoltaic calibration laboratories for 20 years. We calibrate reference modules for production lines and check compliance with the guaranteed performance according to international standards with selected random samples.

Boris Farnung, Tobias Gandy, Martin Jantsch, Martin Kaiser, Jürgen Ketterer, Klaus Kiefer, Ulli Kräling, Carlos Moschella, **Frank Neuberger**, Michael Schachtner, **Gerald Siefer**, Mark Tröscher

Accurate calibration of modules plays an important role in research and development, as well as production. It is essential for module manufacturers, investors and operators of PV power plants. In addition to accurate power measurement, we offer the development of measurement standards for new technology, the characterisation of complete solar simulators in production lines and further development of their components. The highly accurate measurement technology developed at Fraunhofer ISE is applied in these services.

In addition to our solar simulators, we have further equipment available, including light-soaking units, outdoor test stands and spectrometers for complete characterisation of PV modules. Furthermore, electroluminescence images of PV can be recorded. They reveal defects such as micro-cracks or contact finger defects which are invisible to the naked eye.

Our long experience in the module calibration sector, combined with modern measurement equipment and efficient work processes allow us to carry out complex, client-specific tasks within a short time.

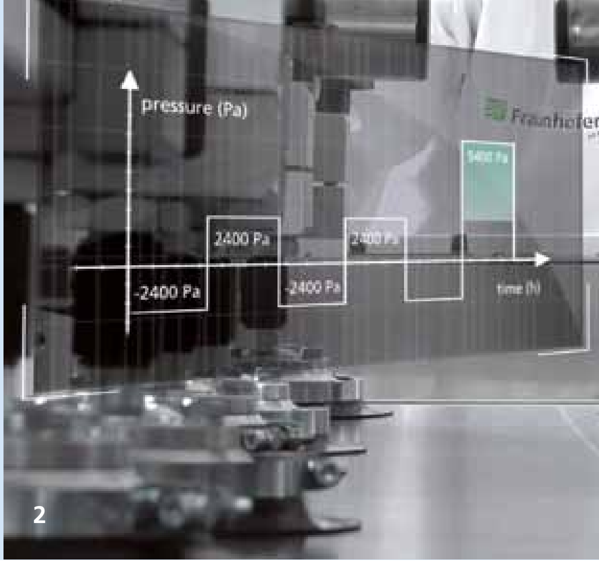
1 *The PV modules are prepared optimally for calibration with modern solar simulator and light soaking units.*

2 *Laboratory test rig to measure concentrator modules, with a parabolic reflector to create a parallel light beam.*

Measurement of concentrator modules

Measurements of concentrator modules are generally made outdoors. To do this, we operate several tracker units equipped with measurement data acquisition, so that all relevant irradiation and meteorological data are recorded in addition to the current-voltage characteristics. In addition, we operate a laboratory test stand to measure concentrator modules. This is based on the provision of parallel light using a parabolic reflector with a diameter of 2 m.

www.callab.de



TestLab PV MODULES EXTENDS ITS INTERNATIONAL TESTING CAPACITY

In 2011, TestLab PV Modules was granted extended new accreditation for the type authorisation of PV modules according to IEC 61215 and IEC 61646 as well as accreditation for the first time concerning the safety standard, IEC 61730. This meant that the testing sequences could be further optimised and the time to test PV modules for type approval has been reduced yet again. The presence and market accessibility of Fraunhofer in the USA was strengthened by establishing a new testing laboratory for PV modules (CFV Solar) in New Mexico as part of a joint venture.

Stefan Ali, Holger Ambrosi, Heinrich Berg, Ilie Cretu, Jürgen Disch, **Claudio Ferrara**, Stephan Hoffmann, Philipp Hog, Michael Köhl, Kerstin Körner-Ruf, Amelie Köpple, Georg Mülhöfer, Daniel Philipp, Carola Völker, Jeannette Wolf

In collaboration with our partner, the VDE Institute, we run the TestLab PV Modules in Freiburg. After successful completion of the module tests, VDE issues the type approval certificate. Beyond the requirements for certification, we develop customised testing sequences together with material manufacturers, module producers and financial institutions for qualification of PV products. High-performance testing facilities, combined with our long years of experience in practice and research, guarantee results of high quality. New testing facilities, both those developed at Fraunhofer ISE and those acquired commercially, make faster tests for certification and tests according to clients' specifications for R&D projects feasible and allow support to accompany development.

As part of the new accreditation, the accredited scope of TestLab PV Modules was extended to cover IEC 61730, the safety standard for PV modules. This step allows further optimisation of the testing sequences and spatial consolidation of the test facilities. In addition to expanding the characterisation and testing capacity, resulting in shorter test times, we also developed new and improved test equipment. This serves the investigation of combined effects, which allows further reduction in the testing time required and more accurate information on the long-term performance of PV modules. One of the newly developed test facilities is a UV radiation unit, which was developed for simultaneous operation in a damp-heat climatic chamber (Fig. 1).

1 *In the combined UV and damp-heat climatic chambers, PV modules can be subjected to a maximal UV dose of 250 Wm^{-2} under maximum conditions of 60 % relative humidity and 90 °C temperature for accelerated aging and testing.*

2 *Mechanical-load test facility. With it, tests conforming to IEC standards and tests which go beyond these can be carried out automatically (maximum pressure and suction of 10 kPa).*

To strengthen our global presence and to diversify our high-quality testing services, we have equipped a further testing laboratory for PV modules in Albuquerque, New Mexico (USA) and taken it into operation. The joint venture with the Canadian Standards Association (CSA), the VDE Institute and Fraunhofer CSE in Boston has created excellent conditions to intensify co-operation on international module testing. With its high proportion of direct solar radiation throughout the year, the site of Albuquerque also offers ideal conditions to test and develop PV modules based on concentrator technology.

Together with the VDE Institute, we run an enterprise in Singapore which offers testing and certification services for PV modules. VDE-ISE Pte. Ltd. is cooperating with the Solar Energy Research Institute of Singapore (SERIS) to support the expansion of solar technology in Asia.

www.testlab-pv-modules.com

TESTING AND DESIGN SUPPORT IN TestLab SOLAR THERMAL SYSTEMS

TestLab Solar Thermal Systems is authorised by DIN CERTCO, CERTIF and SRCC, and is fully accredited according to ISO 17025 by DAkkS (Deutsche Akkreditierungsstelle). We test solar collectors, storage tanks and complete systems, thereby supporting our clients around the world in developing solar thermal system components.

Sven Fahr, **Korbinian Kramer**, Stefan Mehnert, Simon Notz, Rahel Ott, Jens Richter, Arim Schäfer, Christian Schmidt, Christoph Thoma

We accompany our clients in the product certification process, e.g. for the European quality label, Solar Keymark, or the American quality label of the Solar Rating and Certification Corporation SRCC. We also offer on-site inspection of production as part of a contract to prepare such certification.

In 2011, we worked intensively on revising the relevant series of standards. In this context, progress was made in empirical validation and the development of methodology, including that to characterise the combination of solar thermal systems and heat pumps, concentrating collectors and PCM storage units. Another important topic was the testing of heat pipes. A test unit to analyse the response behaviour and the transferred power was completed.

Comparative investigations of PVT collectors were continued. A methodology to characterise many variants of this technology is thus available at TestLab Solar Thermal Systems.

Long and intensive work on our solar air-heating collector test stand was completed. With it, it is now possible to offer similar technical characterisation to that for collectors with liquid heat-transfer media. The extension to the testing facilities for solar air-heating collectors without covers was started.

1 A / B *Outdoor tests as part of the complete testing of solar-thermal collectors in TestLab Solar Thermal Systems.*

System investigations according to DIN EN 12976-1,2:2006 can be carried out with up to four complete hot-water systems in parallel. In addition, storage tanks can be characterised according to DIN EN 12977-3:2008 in the laboratory.

We have operated an indoor test stand with a solar simulator in TestLab Solar Thermal Systems since 2002. Due to the high reproducibility of the measurement conditions, we can carry out targeted developmental work to improve collector constructions very efficiently.

In combination with our precision tracker, we applied our medium-temperature test stand to measure efficiency characteristic curves for operating points up to 200 °C. This means that experimental development work on concentrating process-heat collectors (e.g. for solar-thermally driven air-conditioning) is feasible in TestLab Solar Thermal Systems.

In 2011, many methodological further developments were introduced by our staff members to standardisation committees and will be implemented in new standards. In this way, TestLab Solar Thermal Systems lives up to its intention not only to conduct tests but also to define and set standards.

www.kollektortest.de

1

MEASUREMENT OF BUILDING FAÇADES AND TRANSPARENT COMPONENTS

TestLab Solar Façades offers a comprehensive range of characterisation for innovative building components and materials to developers, manufacturers and planners of façades, façade components and solar components. Special laboratories are available to determine the optical and thermal properties of transparent components and sun-shading systems. For façades for active use of solar energy (with photovoltaic and/or solar-thermal components), we offer comprehensive characterisation, which also includes the interaction between yield, comfort and passive solar gains. Further facilities include a daylighting measurement container and an outdoor test unit.

Ulrich Amann, Johannes Hanek, Angelika Helde,
Tilmann Kuhn, Jan Wienold, Helen Rose Wilson

We characterise transparent and translucent materials. We test building components, e.g. glazing units, and evaluate the energy-relevant, thermal and optical properties of complete façades.

The following measurement facilities are available:

- solar calorimeter to determine the total solar energy transmittance, also for active-solar façades
- efficiency measurement
- thermal transmittance measurements (U value) of glazing units
- angle-dependent transmittance and reflectance measurements with large integrating spheres, both broadband and spectral
- UV-vis-NIR spectrometers to determine the spectral properties of glass, films and surfaces

1 *Solar calorimeter at Fraunhofer ISE to determine the total solar energy transmittance (g value).*

The laboratory has been accredited according to DIN EN ISO/IEC 17025 since 2006. It is a so-called "flexible accreditation", which encompasses not only standard procedures but also the further-reaching procedures developed at Fraunhofer ISE to determine g value, transmittance, reflectance and U value. The German building code recognises our laboratory's determination of the g value (total solar energy transmittance). Some of the development of testing procedures was publicly funded.

Daylighting measurement rooms

The daylighting measurement rooms consist of two identical office rooms, located side-by-side in a container. They can be rotated, so that any desired façade orientation can be chosen.

- glare protection tests
- user acceptance studies
- comparison of the lighting situation behind two façade systems

Façade testing facility

In addition to laboratory measurements, we offer the measurement of complete façades under real climatic conditions. Long-term investigations provide information on the stability, switching performance and loads on the façade. The optimisation of controllers can be experimentally validated.

Quality Assurance of PV Power Plants

The four phases of the Fraunhofer ISE quality cycle – yield assessment, module characterisation, system testing and quality monitoring – guarantee comprehensive quality assurance of PV power plants.

- Our quality assurance services start already in the planning phase of a PV system. The anticipated yields are predicted reliably in our yield assessments.
- If a PV system has commenced operation, its quality can be controlled with comprehensive on-site analysis that includes visual inspection, thermography and determination of the actual power generated.
- Our customised PV monitoring offers accurate analysis of the component and system efficiency over the complete service lifetime of a PV power plant.

Klaus Kiefer, Anselm Kröger-Vodde, Frank Neuberger, Nicole Römer, Andreas Steinhüser

1 *10 MW_p solar power station in Masdar, Abu Dhabi.*

Battery Test Laboratory

We test batteries and battery systems based on lead-acid, NiCd, NiMH and Li ion cells, as well as high-temperature batteries and double-layer capacitors. Battery testing systems and impedance spectrometers are available for use either according to the procedures specified by the relevant standards (DIN, IEC, PVGAP and others), or in a climatic chamber or a water bath according to clients' specifications.

Long-term tests

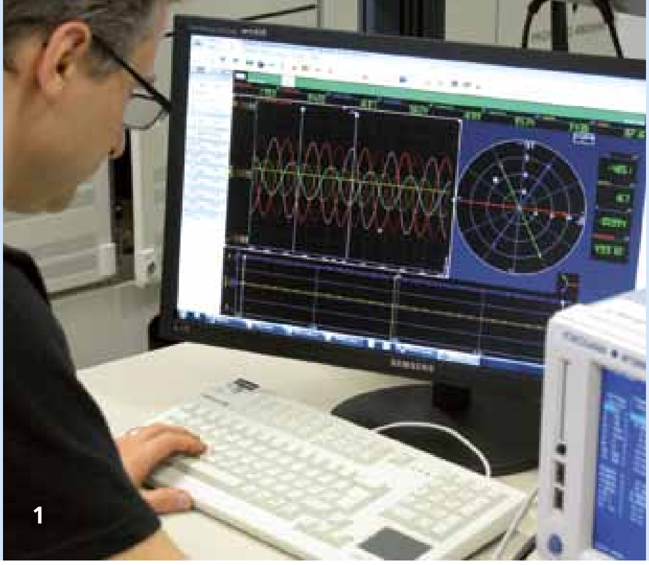
We also offer long-term tests lasting several months as lifetime tests for batteries and battery systems, in which the load and temperature profiles can be selected as required.

Automotive sector

We test systems up to a power of 250 kW with currents up to 600 A and voltages up to 1000 V. The test object can be controlled via a CAN bus and subjected to driving cycles. As a safety precaution, the battery system is tested in a climatic chamber that is filled with inert gas and is equipped with a fire-extinguishing system.

Georg Bopp, Nikolaus Lang, **Stephan Lux**, Stefan Rinne, Simon Schwunk, Matthias Vetter

2 *In the climatic chamber, not only efficiency and capacity but also the aging and charging performance of storage batteries can be investigated under variable conditions.*



Inverter Laboratory

Our so-called megawatt laboratory at Fraunhofer ISE is equipped with all of the facilities which are needed to test inverters up to a power rating of 1 MW according to national and international grid codes. A test facility for "low voltage ride through tests" on the medium-voltage side enables us to investigate the reaction of inverters to short-term grid faults. These tests are demanded by the German association of electricity and water utilities (BDEW), among others.

Our experienced team competently supports clients with activities in our laboratory. A solar-generator simulator with a power of up to 1.3 MW and our highly accurate measurement technology makes it possible to determine not only the conversion efficiency of inverters but also their MPP tracking behaviour.

Bruno Burger, **Sönke Rogalla**

Lighting Laboratory

Characterisation

We carry out accurate measurements of photometric quantities for lamps, lights and lighting systems. These include measurement of the luminous flux, the luminous efficacy and the illuminance distribution, and investigations of the operating performance of the lighting technology under different conditions. We also determine the electrical properties of electronic controls and electronic ballasts, including the efficiency, operating behaviour and fault management.

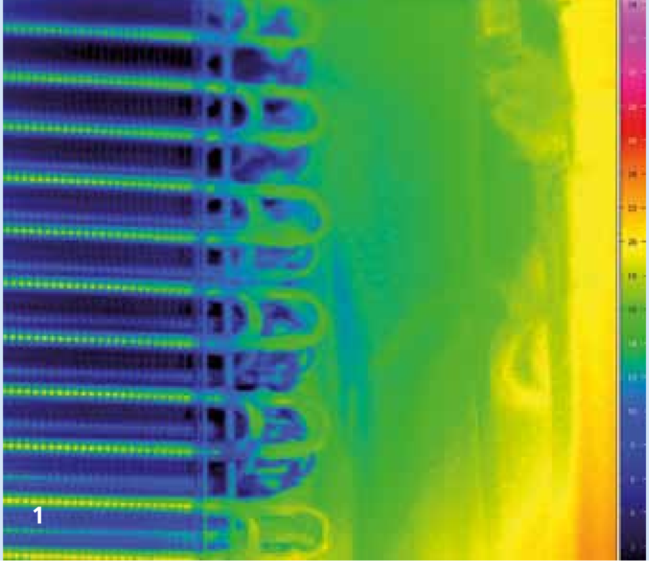
Equipment

- software-controlled lighting measurement stand with an integrating sphere of 1.50 m diameter and spectrometers
- a luminance camera, luxmeters and long-term test stands
- accurate broadband wattmeters, digital oscilloscopes
- programmable stabilised power supplies.

Georg Bopp, **Norbert Pfanner**

1 *Our equipment and our experienced team enable detailed analysis of module inverters, string inverters and central inverters up to a power rating of 1 MW with regard to performance and grid behaviour.*

2 *Integrating sphere in the lighting laboratory to determine the luminous flux, the luminous efficacy and the long-term performance of light sources and lamps.*



Test Facility for Heat Pumps and Evaporators

Over the past two years, testing facilities for heat pumps and evaporators with small capacities have been established at Fraunhofer ISE. A test rig for air-charged evaporators has recently been commissioned which can use additional heat sources.

We operate a test rig to measure heat pumps. The heat pump test facility is equipped for heating power from 4 kW up to 12 kW. The heat sources can be glycol-water, water or air – as individual sources or also in combination with each other – and the heat sinks can be air or water. The measurements are mostly made in parallel to component development and are conducted according to EN 14511, EN 14825 and if required, also still according to EN 255-3 or EN 16147. However, these latter tests are carried out without official certificates being issued.

Marek Miara, **Thore Oltersdorf**, Jeannette Wapler

PCM Laboratory: Characterisation of Latent-Heat Storage Materials

In the PCM laboratory, the enthalpy-temperature characteristic and the phase-transition reproducibility of phase-change materials, composites, components and systems are tested according to the criteria of the quality seal, RAL GZ 869. The laboratory is an authorised certification body for this quality seal Measurement instruments to determine the following material parameters are available:

- thermal conductivity and thermal transmittance (U value) of building components and wall constructions
- specific and latent heat storage capacity, nucleation temperature and supercooling by Calvet and heat-flux differential scanning calorimetry (DSC)
- cycling equipment
- test room constructed according to DIN EN 14240 for static and dynamic measurement of surface heating and cooling systems, including those which contain PCM
- test rooms with outdoor surfaces to measure PCM systems
- specially for phase change slurries (PCS):
  - density
  - thermal conductivity
  - particle size
  - viscosity
  - stability analysis
- test stands to prepare, characterise and cycle emulsions

Stefan Gschwander, **Thomas Haussmann**, Peter Schossig

1 *Thermograhic image of a 3-fluid evaporator with glycol-water flowing through internal pipes along the pipe axes and around the bends, and external pipes and fins that are surrounded by air and have been cooled down by evaporation.*

2 *Surface heating and cooling systems are measured under dynamic and static load profiles in a large adiabatic test room of dimensions 4 m x 4 m x 3 m, which has been constructed at Fraunhofer ISE according to DIN EN 14240.*

Test Laboratory for Adsorption Materials and Porous Materials

The laboratories for thermal and structural analysis offer a broad spectrum of analytical methods to characterise porous materials.

Our facilities include equipment for gas sorption measurements with various test gases (N_2, CO_2, EtOH, MeOH, H_2O) to determine the surface area, pore properties and adsorption characteristics with volumetric methods. In addition, thermogravimetric methods are available for H_2O, EtOH and MeOH as the measurement gases. Instruments for mercury intrusion measurements and helium pycnometry round out our range of services. Various calorimeters as well as a laser-flash system are available to determine heat capacity and thermal conductivity. The methods to investigate morphology include optical and laser-scanning microscopy, as well as X-ray powder diffractometry.

Stefan Henninger, Peter Schossig

TestLab Fuel Cells

We characterise and test membrane fuel cells and systems with an electric power rating up to 5 kW_{el} as well as miniature fuel cells. In co-operation with the VDE Testing and Certification Institute, we offer consultancy services, tests according to standards and certification.

In the characterisation of fuel cells, we particularly emphasise the detailed investigation of local processes. With the help of electrochemical impedance spectroscopy, we can analyse the individual chemical-physical processes with regard to their dependence on material properties, construction and operation management.

Our walk-in climatic chamber allows investigations to be carried out over the temperature range from -20 °C to +60 °C. The relative humidity can be varied at temperatures above +5 °C between 10 % and 95 %. The high throughput of conditioned air, up to 2000 m^3 per hour, is notable.

Dietmar Gerteisen, **Ulf Groos**, Jürgen Wolf,

1 *Thermal balance to determine the water vapour adsorption capacity of large composite samples as a function of pressure and temperature.*

2 *Climatic chamber to characterise fuel cell stacks and systems with an electric power rating up to 5 kW_{el}.*

APPENDIX

VISITING SCIENTISTS

Luis Barrera Aguilar
Universidad Popular Autonoma del Estado de Puebla, Puebla, Mexico, 1.9.–30.12.2011
Research area: Investigation of PV-hybrid systems and the use of simulation tools

Matteo Balestrieri
Università di Bologna, Bologna, Italy, 16.10.2009–28.2.2011
Research area: Analysis of silicon surfaces with SPV

Erika Biserni
Politecnico di Milano, Milano, Italy, 1.6.2010–30.9.2011
Research area: Laser Chemical Processing (LCP)

Dr Alfa Oumar Dissa
Université de Ouagadougou, Ouagadougou, Burkina Faso, 19.9.–18.10.2011
Research area: Solar thermal energy

Karoline Fath
Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany 1.11.2010–31.10.2013
Research area: Life cycle analysis of building-integrated PV systems

Simon Fey
Promotionskolleg »KleE – Kleinskalige erneuerbare Energiensysteme«, Hochschule Offenburg, Offenburg, Germany, 1.9.2011–31.7.2014
Research area: Energy gateway

J. Ignacio Torrens Galdiz, M. Sc.
National University of Ireland Galway, Galway, Ireland 1.2.–31.7.2011
Research area: Building operating management

Mónica Delgado Gracia
Universidad de Zaragoza, Zaragoza, Spain, 1.9.–30.11.2011
Research area: Latent thermal storage

Antanas Katalevskis
Kaunas University of Technology , Kaunas, Lithuania, 1.2.2011–31.1.2012
Research area: Fe-Imaging with photoluminescence

Alexander V. Mellor
Universidad Politécnica de Madrid, Madrid, Spain, 1.6.–30.11.2011
Research area: Photonic structures for solar cells

Amada Montesdeoca-Santana, Universidad de La Laguna Tenerife, Spain, 1.9.2008–31.7.2011
Research area: Silicon solar cells

Amir Nashed
Alexandria, Egypt, 1.9.–31.12.2011
Research area: Solar desalination of sea water

Prof. Uwe Nuss
Hochschule Offenburg, Offenburg, Germany, 1.10.2010–31.1.2011
Research area: Controls for PV inverters

Francesco Passerini
Università degli Studi di Trento, Trento, Italy, 16.7.2010–15.4.2011
Research area: Energy-efficient buildings

Pheng Phang
Australian National University, Canberra, Australia 1.2.–28.5.2011
Research area: Microphotoluminescence spectroscopy and simulation

Seok-Jun Seo
Gwangju Institute of Science and Technology (GIFT), Gwangju, South Korea, 1.3.2011–28.2.2012
Research area: Electrochemical properties of porous substrates for dye solar cells

Dr Nada Zamel
University of Waterloo, Waterloo, Canada, 1.10.2011–30.9.2013
Research area: Water management and fuel cells

CONGRESSES, CONFERENCES AND SEMINARS

Workshop SiliconFOREST
Falkau, Germany, 27.2.–2.3.2011

26. Symposium Photovoltaische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 2.–4.3.2011

Workshop "Batteriesystemtechnik", Fraunhofer-Forum Berlin, Germany, 15.3.2011

CPV-7 – International Conference on Concentrating Photovoltaic Systems, Las Vegas, NV, USA, 4.–6.4.2011

Workshop "PV-Module Reliability", Berlin, Germany, 5./6.4.2011

SiliconPV – 1st International Conference on Silicon Photovoltaics, Freiburg, Germany, 17.–20.4.2011

21. Symposium Thermische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 11.–13.5.2011

Berliner Energie-Tage , Berlin, Germany, 20.5.2011

15th Am0-Workshop on Space Solar Cell Calibration and Measurement Techniques, Freiburg, Germany, 31.5.–3.6. 2011

Fachforum "Quality of PV-Systems" (OTTI), Munich, Germany, 6.6.2011

Intersolar Europe Conference 2011, Munich, Germany, 6.–10.6.2011

7th Advanced PV Manufacturing Forum, Munich, Germany, 7.6.2011

37th IEEE Photovoltaic Specialist Conference, Seattle, WA, USA, 19.–24.6.2011

8th Credit Suisse Salon, Zurich, Switzerland, 5.7.2011

6th Seminar Power Electronics for Photovoltaics (OTTI)
Munich-Dornach, Germany, 6./7.7.2011

1st Seminar Power Electronics for Photovoltaics, San Francisco, CA, USA, 11.7.2011

Intersolar North America Conference 2011, San Francisco, CA, USA, 11.–14.7.2011

ISES Solar World Congress, Kassel, Germany, 28.8.–2.9.2011

26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 5.–9.9.2011

Workshop "ModQS – Automatisierte Fehlerdiagnose in Heizungssystemen", Hamburg-Harburg, Germany, 14.9.2011

Workshop "Ladesysteme für Elektrofahrzeuge – Konzepte und Anforderungen", Fraunhofer-Forum Berlin, Germany, 27.9.2011

4. VDI-Fachtagung "Solarthermie – Heizen und Kühlen mit der Sonne", Ludwigsburg, Germany, 27./28.9.2011

Fachforum "Netzferne Stromversorgung mit Photovoltaik" (OTTI), Freiburg, Germany, 4./5.10.2011

FVEE-Jahrestagung , Berlin, Germany, 12./13.10.2011

4th Conference Solar Air-Conditioning (OTTI), Larnaca, Cyprus, 12.–14.10.2011

Solar Summit Freiburg , Freiburg, Germany, 14./15.10.2011

2nd European Conference SmartGrids and E-Mobility (OTTI), Munich, Germany, 17./18.10.11

5th European Solar Thermal Energy Conference, Marseille, France, 20./21.10.2011

6th International Renewable Energy Storage Conference and Exhibition, Berlin, Germany, 28.–30.11.2011

Fraunhofer ISE organised or co-organised the congresses, conferences and seminars listed above.

DOCTORAL THESES

Jonas Bartsch, "Advanced front side metallisation for crystalline silicon solar cells with electrochemical techniques", Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Patrick Dupeyrat, "Experimental development and simulation investigation of a photovoltaic-thermal hybrid solar collector", L'Institut National des Sciences Appliquées de Lyon, Lyon, 2011

Jara Fernández, "Development of crystalline germanium for thermophotovoltaics and high-efficiency multi-junction solar cells", Universität Konstanz, Konstanz, 2010

Paul Gundel, "Neue mikroskopische Opto-Spektroskopie-Messmethoden für die Photovoltaik" (New optical microspectroscopy measurement methods for photovoltaics), Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Holger Habenicht, "Charakterisierung leistungsmindernder Defekte und deren Umverteilung während der Herstellung von multikristallinen Silizium-Solarzellen" (Characterisation of performance-reducing defects and their redistribution during the manufacture of mc silicon solar cells), Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Jochen Hohl-Ebinger, "Untersuchungen zur hochpräzisen Vermessung der elektrischen Parameter von Solarzellen", (Investigation on high precision measuring of the electric parameters of solar cells), Universität Konstanz , Konstanz, 2011

Sybille Hopman, "Anwendung des Laser Chemical Processing zur Herstellung von Silizium-Solarzellen", (Use of laser chemical processing for manufacturing silicon solar cells), Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Michael Köhl, "Grundlegende Untersuchungen zur Gebrauchsdaueranalyse von Photovoltaik-Modulen", (Basic investigations on lifetime analysis of photovoltaic modules), FernUniversität Hagen, 2011

Joachim Koschikowski, "Entwicklung von energieautark arbeitenden Wasserentsalzungsanlagen auf Basis der Membrandestillation", (Development of energy autonomous desalination systems based on membrane distillation), Universität Kassel, Kassel, 2011

Matthias Künle, "Silicon carbide single and multilayer thin films for photovoltaic applications", Universität Tübingen, Tübingen, 2011

Timo Kurz, "Entwicklung eines Hochtemperatur-PEM-Brennstoffzellen-Systems auf Basis von PBI-Membranen zur effizienten Verstromung biogener Reformatgase", (Development of a high temperature PEM fuel cell system based on PBI-membranes for efficient conversion of biogenic reformate gas to electricity), Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Gerhard Peharz, "Hocheffiziente photovoltaische Konzentratormodule: Untersuchung von Einflußfaktoren und Energieertragsmodellierung", (High-efficiency photovoltaic concentrator modules: Investigation of the influencing factors and energy yield modelling), Universität Konstanz, Konstanz, 2011

Damian Pysch, "Assembly and analysis of alternative emitter systems for silicon solar cells", Universität Konstanz, Konstanz, 2011

Christian Reichel, "Decoupling charge carrier collection and metallization geometry of back-contacted back-junction silicon solar cells", Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

Jonas Schön, "Modellierung von Prozessschritten zur Umlagerung rekombinationsaktiver Defekte in kristallinem Silizium" (Modelling of processing steps for the redistribution of recombination-active defects in crystalline silicon), Universität Konstanz , Konstanz, 2011

Dominik Suwito, "Intrinsic and doped amorphous silicon carbide films for the surface passivation of silicon solar cells", Universität Konstanz, Konstanz, 2011

Joachim Went, "Untersuchung zur Verbesserung der Mikro-/Ultrafiltration durch Ultraschall" (Investigation to improve the micro- or ultrafiltration by means of ultrasound), Technische Universität Kaiserslautern, Kaiserslautern, 2011

Bernhard Wille-Haussmann, "Einsatz der symbolischen Modellreduktion zur Untersuchung der Betriebsführung im Smart Grid" (The use of symbolic model reduction to investigate the operation management in the smart grid), FernUniversität Hagen, Freiburg, 2011

Martin Zimmer, "Nasschemische Prozesse bei der Herstellung von kristallinen Siliciumsolarzellen und deren Analytik" , (Analysis of wet-chemical processes in crystalline silicon solar cell production) Albert-Ludwigs-Universität Freiburg, Freiburg, 2011

PROMOTION OF YOUTH

Fraunhofer ISE is also active in recruiting youth for the scientific and engineering fields. We organise numerous on-going events in which our scientists actively partake. Through these, we strive to foster enthusiasm in today's youth for the topic of renewable energy. Further, the activities offer young people the possibility to gain insight about educational training possibilities and employment at an early stage.

Girls' Day 2011

Again in 2011, Fraunhofer opened its doors for the nationwide "Girls' Day". Twenty students were offered the possibility to experience a closer look at the research and development work at our institute. In different laboratories at the Institute, the girls performed experiments in small groups under the direction of Fraunhofer scientists and gained insight into the daily life of a physicist working in the area of renewable energy. At the end of the day, the girls proudly presented their results to the group.

www.girls-day.de

Umwelt-Talent School 2011

From 2–4 November 2011 the "Umwelt-Talent School" took place for the first time at Fraunhofer ISE. Experienced scientists relayed theoretical and practical know-how on the subject of solar energy. Students in classes 9 through 12/13, interested in science and technology, attended. In workshops the students worked together meticulously on their inventions. The topics covered included solar power generation, solar energy concentration and the optical technology for solar applications. In addition to the practical work, Fraunhofer ISE also offered an informative and varied program around the event. The successful event carried out in cooperation with the Deutsche Bundesstiftung Umwelt (DBU) is to be continued over the next three years.

Activity in schools

The co-operative action, started in 2010 with Solare Zukunft e.V., was also continued into 2011. Together with Solare Zukunft e.V., young scientists from Fraunhofer ISE visited the physics courses at schools throughout the Freiburg area who applied to the program. The Fraunhofer scientists presented their own educational experiences and daily job responsibilities. Solar energy topics were demonstrated using hands-on experiments. The event offered a welcome change from the normal course work.

PATENTS GRANTED

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"Fuel Cell System in the Form of a Printed Circuit Board": Schmitz, Andreas; Hebling, Christopher; Hahn, Robert; Burger, Bruno, JP 4745611

"Method for simultaneously recrystallising and doping semi-conductor and semi-conductor system produced according to said method": Reber, Stefan, EP 1 792 349 A1

"Modified Hopcalit catalyst: method for its manufacture and the use thereof": Susdorf, Alexander; Hübner, Peter; Chigapov, Albert; Carberry, Brendon, DE 10 2006 018 529 A1

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"Circuit breaker for a solar module": Burger, Bruno; Schmidt, Heribert, EP 1 884 008 A1

"Method for operating a direct oxidation fuel cell and corresponding arrangement": Eccarius, Steffen; Litterst, Christian; Koltay, Peter, EP 1 964 198 A1

"Direct oxidation fuel cell and method for operation thereof" Eccarius, Steffen; Litterst, Christian; Koltay, Peter, US 2009/0017357 A1

"Inverter with integrated controller and regulator for a tracker": Burger, Bruno; Lerchenmüller, Hansjörg, EP 2 100 199 A1

"Cell connector for electronically contacting planar power sources, and use": Wirth, Harry, US 2009/0318037 A1

"Method for metallising semiconductor elements and use thereof": Grohe, Andreas; Nekarda, Jan-Frederik; Schultz-Wittmann, Oliver, US 2009/0221112 A1

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"Fuel cells and method for the manufacturing thereof": Oszcipok, Michael; Eccarius, Steffen, DE 10 2007 014 046 A1

"Solar element with increased efficiency and method for increasing efficiency": Goldschmidt, Jan Christoph; Löper, Philipp; Peters, Marius, EP 2 195 859 A2

"Bipolar plate for a PEM electrolyser": Hacker, Beatrice; Jungmann, Thomas; Wittstadt, Ursula; Smolinka, Tom, EP 2 201 157 A1

"Controllable switch-over device for a solar module": Burger, Bruno; Schmidt, Heribert, EP 2 179 451 A1

"Fluid distribution element for a flow directing device, especially for nested multi-channel flow directing devices": Sicre, Benoit; Oltersdorf, Thore; Hermann, Michael, DE 10 2007 056 995 A1

"Measuring device for electrically measuring a flat measurement structure that can be contacted on one side": Glatthaar, Markus; Rein, Stefan; Biro, Daniel; Clement, Florian; Menkö, Michael; Krieg, Alexander, DE 10 2009 012 021 A1

"Method for determining a structure of a semiconductor material having predefined opto-electrical properties, method for the production thereof, and semiconductor material": Peters, Marius; Bläsi, Benedikt; Goldschmidt, Jan Christoph, DE 10 2010 008 905 B3

LECTURE COURSES AND SEMINARS

University of Freiburg
Dr Stefan Glunz
"Photovoltaische Energiekonversion", Lectures SS 11,
Faculty of Engineering

Dr Stefan Glunz, Dr Martin Schubert, Dr Harry Wirth
"Crystalline Silicon Photovoltaics", Lectures SS 11,
Master Online Photovoltaics (MOPV)

Dr Stefan Glunz, Dr Uli Würfel
"Fundamentals of Solar Cells", Lectures WS 11/12,
Master Online Photovoltaics (MOPV)

Dr Peter Kailuweit
"Selected Semiconducter Devices", Seminar WS 10/11
Master Online Photovoltaics (MOPV)

Dr Werner Platzer
"Elective II – Energy Efficiency and Solar Thermal Energy", Lectures
Module WS 11/12, Zentrum für Erneuerbare Energien (ZEE)
University Course: Renewable Energy Management (REM)

Dr Werner Platzer, Dr Ralf Preu, Dr Christof Wittwer
"Technology I", Lectures WS 10/11, Zentrum für Erneuerbare
Energien (ZEE), University Course: Renewable Energy
Management (REM)

Dr Olivier Stalter
"Fundamentals of PV Systems", Lectures WS 10/11 + WS 11/12,
Master Online Photovoltaics (MOPV)

Dr Olivier Stalter
"Electrical Engineering and PV Power Electronics",
Lectures WS 11/12, Master Online Photovoltaics (MOPV)

Prof Dr Eicke R. Weber, Dr Werner Platzer, Korbinian Kramer
"Solarthermie", Lectures WS 2011/12, Faculty of Physics and
Mathematics

Prof Dr Eicke R. Weber, Dr Uli Würfel
"Photovoltaische Energiekonversion", Lectures SS 2011,
Faculty of Physics and Mathematics

Prof Dr Eicke R. Weber, Dr Uli Würfel
"Photovoltaik", Seminar SS 2011 and WS 2011/12,
Faculty of Physics and Mathematics

Dr Christof Wittwer
"Smart Grid and Autonomous Communities", Lectures WS 11/12,
Master Online Photovoltaics (MOPV)

Baden-Wuerttemberg Cooperative State
University (DHBW), Ravensburg
Prof Bruno Burger
"Solar-Technologien", Lectures SS 11, Electrical Engineering –
Automation

M. Eng. Dirk Kranzer
"Leistungselektronik", Lectures WS 10/11, Electrical Engineering –
Automation

Hector School, Karlsruhe
Prof Dr Bruno Burger
"Green Mobility Engineering – Power Electronics",
Lectures WS 11/12

University of Applied Sciences, Offenburg
Dr Thomas Aicher
"Chemie", Lectures WS 11/12, Energy System Technology

Dr Doreen Kalz
"Wärme- und Raumlufttechnik", Lectures SS 11, Process Engineering

Norbert Pfanner
"Solartechnologie", Lectures SS 11,
Electrical Engineering/Information Technology^{Plus}

Dr Achim Schaadt
"Energieverfahrenstechnik", Lectures WS 10/11,
Electrical Engineering/Information Technology^{Plus}

LECTURE COURSES AND SEMINARS

KIT Karlsruhe Institute for Technology
Prof Dr Bruno Burger
"Leistungselektronische Systeme für regenerative Energiequellen", Lectures WS 11/12, Faculty for Electrical Engineering and Information Technology

Dr Heribert Schmidt
"Photovoltaische Systemtechnik", Lectures SS 11, Faculty for Electrical Engineering and Information Technology

Stuttgart State Academy of Art and Design, Stuttgart
Florian Kagerer
"Bauökologie/Energie effizientes Bauen", Lectures SS 11, Architecture

College of Applied Science, Georg Agricola zu Bochum
Dr Dietmar Borchert
"Photovoltaik", Lectures SS 11, Faculty of Machine Technology

University of Kassel
Brisa Ortiz
"Hybrid System Simulation", Seminar SS 10 and WS 10/11, European Master in Renewable Energy

University of Koblenz-Landau
Dr Jens Pfafferott
"Solares Bauen", Presence Seminars SS 10 and WS 10/11
Distant-Learning Course: Energy Management

In addition to the teaching activities at colleges and universities listed here, scientists at Fraunhofer ISE regularly lead practical workshops and teach courses of further study for people from the finance sector and industry. For example, in the series "PV Training" we offer seminars and workshops on silicon technology or in the OTTI seminar "Off-Grid Power Supply" we provide our knowledge on the products, planning and construction of remote electrical power systems.

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»Quantum Efficiency in Complex Systems, Part I: Biomolecular Systems«, in: Semiconductors and Semimetals Vol. 83, Elsevier, Academic Press, New York, 2010, ISBN 978-0-12-375042-6

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INVITED TALKS

Invited talks at international conferences and workshops

Alink, R.; Henninger, S.; Schwager, M.; Hügenell, P.; Mérida, W. (University of British Columbia, Vancouver, Canada)
»Water Sorption of Commercial Membrane Electrode Assemblies«, ECS Binual Meeting, Electrochemical Society, Montreal, Canada, 3.5.2011

Bett, A. W.
»Hochkonzentrierende Photovoltaik: Entwicklungsstand und Perspektiven«, Arbeitskreis Energie 2011, DPG-Jahrestagung, Dresden, Germany, 14.–17.3.2011

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»III-V-Based Multi-Junction Solar Cells Used in Space and Concentrator PV«, German Polish Conference on Crystal Growth (GPCCG) 2011, DGKK, Frankfurt (Oder)/Slubice, Germany, 14.–16.3.2011

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»Thick Film Metallization for Contacting Emitters with High Sheet Resistance – Current Technologies and New Approaches«, 3rd Workshop on Metallization for Crystalline Silicon Solar Cells, Charleroi, Belgium, 24.–26.10.2011

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Rau, S.; Fuentes, R. (University of South Carolina, Columbia, SC, USA); Smolinka, T.; Weidner, J. (University of South Carolina, Columbia, SC, USA)
»Geträgerte nano-strukturierte Katalysatoren für eine hocheffiziente Wasserstoffproduktion mittels PEM-Elektrolyse«, Brennstoffzellen – Materialien und Systeme, AGEF e.V. & Fraunhofer ICT, Pfinztal, Germany, 22./23.3.2011

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Rogalla, S.
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»Fertigungs- und betriebsoptimierte Brennstoffzellenstapel«, Brennstoffzellen – Materialien und Systeme, AGEF e.V. & Fraunhofer ICT, Pfinztal, Germany, 22./23.3.2011

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»Metal Pinning through Rear Passivation Layers: Characterization and Effects on Solar Cells«, 1st International Conference on Silicon Photovoltaics 2011, Freiburg, Germany, 17.–20.4.2011

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»Screen Printed Al-Pastes for LFC Solar Cells«, 3rd Workshop on Metallization for Crystalline Silicon Solar Cells, Charleroi, Belgium, 24.–26.10.2011

Smolinka, T.; Garche, J. (FCBAT, Ulm, Germany)
»Stand und Entwicklungspotenzial der Wasserelektrolyse«, Strategieplattform Power to Gas – Workshop Elektrolyse, DENA, Berlin, Germany, 18.10.2011

Smolinka, T.; Garche, J. (FCBAT, Ulm, Germany); Hebling, C.; Ehret, O. (NOW, Berlin, Germany)
»Water Electrolyser for Hydrogen Storage – Study on State of the Art of the Technology and Future Development Trends«, 6th International Conference on Renewable Energy Storage 2011, EuroSolar e.V., Berlin, Germany, 28./29.11.2011

Smolinka, T.; Garche, J. (NOW GmbH, Berlin, Germany)
»Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien«, NOW-Workshop Elektrolyse, NOW GmbH, Berlin, Germany, 9.5.2011

Smolinka, T.; Rau, S.; Ojong, E. T.; Hebling, C.
»Cell and Stack Design for High Pressure Operation of PEM Water Electrolyzers«, Hydrogen + Fuel Cells 2011, Canadian Hydrogen and Fuel Cell Association, Vancouver, Canada, 15.–18.5.2011

Stryi-Hipp, G.
»Solar Thermal Technology for Heating and Cooling: Market Perspectives and Research Topics – Flat Plate Collectors – Principles for Design«, Energy Workshop 2011, US Army, Las Vegas, NV, USA, 28.1.2011

Thaidigsmann, B.; Lohmüller, E.; Spribille, A.; Linse, M.; Mack, S.; Jäger, U.; Pospischil, M.; Eitner, U.; Haunschild, J.; Wolf, A.; Clement, F.; Clement, F.; Biro, D.; Preu, R.
»MWT Cell Structures for High Efficiency and Low Cost«, MWT Workshop 2011, Freiburg, Germany, 10.11.2011

Vetter, M.
»Dezentrale netzgekoppelte PV-Batteriesysteme«, Elektrische Energiespeicher 2011, VDI, Wiesbaden, Germany, 18./19.5.2011

Weber, E.
»Aussicht der PV in Deutschland und global«, OTTI Regensburg, Kloster Banz, Bad Staffelstein, Germany, 2.3.2011

Weber, E.
»Chancen und Herausforderungen der Solarindustrie nach Fukushima«, 3. Deutsch-Amerikanische Energietage Berlin, Berlin, Germany, 13.5.2011

Weber, E.
»Die Transformation auf ein 100% regeneratives Energiesystem«, Universität Konstanz, 8. Konstanzer Europakolloquium, Konstanz, Germany, 14.5.2011

Weber, E.
»Game Changer: Future Solar Cells based on Low Cost Silicon«, European Future Energy Forum EFEF 2011, Genf, Switzerland, 10.10.2011

Weber, E.
»Nanostructured Systems for Photovoltaic Applications«, International Nano-Optoelectronics Workshop iNOW Conference, Würzburg, Germany, 4.8.2011

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Weber, E.
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Weber, E.
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Weber, E.
»R&D for Renewable Energies«, Deutsch-koreanische Konferenz, Seoul, Korea, 5.10.2011

Weber, E.
»The Role of Material Science for Future Photovoltaics«, German Polish Conference on Crystal Growth GPCCG 2011, Frankfurt/Oder, Germany, 14.3.2011

Weber, E.
»Zukunft der Photovoltaik«, 6. Deutscher Energiekongress, München, Germany, 13.9.2011

Wiesenfarth, M.; Eltermann, F.; Helmers, H.; Steiner, M.; Röder, K.; Dörsam, T.; Siefer, G.; Dimroth, F.; Bett, A. W.
»Co-Generation of Electrical Power and Thermal Energy in CPV Systems«, Spring Conference 2011, EMRS, Nizza, France, 10.5.2011

Wiesenfarth, M.; Jaus, J.; Siefer, G.; Dimroth, F.; Bett, A. W.
»Thermisches Management in der Konzentratorphotovoltaik«, 5. Tagung Elektronikkühlung 2011, Haus der Technik, Stuttgart, Germany, 24.5.2011

CONFERENCES AND TRADE FAIRS – OUTLOOK 2012

PV Rollout
2nd European American Solar Deployment Conference
Boston, MA, USA, 9./10.2.2012

27. Symposium Photovoltaische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 29.2–2.3.2012

Battery Expo
Tokyo, Japan, 29.2.–2.3.2012

Energy Storage
International Summit for the Storage of
Renewable Energies
Düsseldorf, Germany, 13./14.3.2012

SiliconPV
2nd International Conference on Silicon Photovoltaics
Leuven, Belgium, 3.–5.4.2012

CPV-8
8th International Conference on Concentrating
Photovoltaic Systems
Toledo, Spain, 16.–18.4.2012

HANNOVER MESSE
Hanover, Germany, 23.–27.4.2012

22. Symposium Thermische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 9.–11.5.2012

World Hydrogen Energy Conference
Toronto, ON, Canada, 3.–7.6.2012

Woche der Umwelt
Berlin, Germany, 5./6.6.2012

Intersolar Europe
Munich, Germany, 13.–15.6.2012

1st International Conference on Solar Heating
and Cooling for Buildings and Industry
San Francisco, CA, USA, 9.–11.7.2012

Intersolar North America
San Francisco, CA, USA, 10.–12.7.2012

Clean Tech Media Award
Berlin, Germany, 7.9.2012

18th SolarPACES Conference
Marrakesh, Marocco, 11.–14.9.2012

f-cell Forum
Stuttgart, Germany, 24./25.9.2012

27th European Photovoltaic Solar Energy
Conference and Exhibition
Frankfurt, Germany, 24.–28.9.2012

Solar Summit Freiburg
Freiburg, Germany, 18./19.10.2012

The Battery Show
Novi, Detroit, MI, USA, 13.–15.11.2012

PARTICIPATION IN ORGANISATIONS

acatech – Deutsche Akademie der Technikwissenschaften, Member

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Deutsche Gesellschaft für Nachhaltiges Bauen e. V. (DGNB), Member

Deutsche Gesellschaft für Sonnenenergie e. V. (DGS), Member

Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE (DKE)
- *Komitee 373 "Photovoltaische Solarenergiesysteme"*
- *Komitee 384 "Brennstoffzellen"*
- *Arbeitsgruppe "Portable Fuel Cell Systems"*
- *Ad-hoc-Arbeitskreis "Blitz- und Überspannungsschutz für Photovoltaik-Anlagen"*

Deutsche Meerwasserentsalzung e. V. (DME), Member

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Deutsches Institut für Normung e. V. (DIN)
- *Fachnormenausschuss Heiz- und Raumlufttechnik (NHRS AA1.56) "Solaranlagen", Member*
- *Fachnormenausschuss Lichttechnik (FNL 6) "Innenraumbeleuchtung mit Tageslicht", Member*

Energy Conservation in Buildings and Community Systems Programme ECBCS
- *Annex 47 "Cost Effective Commissioning"*

Energy Conservation Through Energy Storage Programme ECES
- *Annex 24 "Compact Thermal Energy Storage – Material Development for System Integration"*

Erfahrungsaustauschkreis der Prüfstellen Thermischer Solaranlagen und ihrer Bauteile EKTSuB des DIN, Deputy Chairman

EU PV Technology Platform
- *Working Group "Science, Technology & Applications" (WG3), Member*
- *Working Group "Developing Countries" (WG4), Member*

Europäisches Komitee für Normung
- *CEN TC33 WG3 TG5, Member*
- *CEN TC129 WG9, Member*
- *CEN TC 169 WG 11 "Daylighting in Buildings", Member*
- *CEN TC312 WG1, WG2, WG3, Member*

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European Committee for Electrotechnical Standardization (CENELEC)
- *TC 82 /WG 0 1 "Wafers, Cells and Modules" – NWIP "BIPV", Chair and Member*

European H2/FC Technology Platform, Member

PARTICIPATION IN ORGANISATIONS

European Photovoltaic Industry Association (EPIA), Associate Member

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European Renewable Energy Research Centres Agency (EUREC), Member

European Solar Thermal Electricity Association (ESTELA), Scientific Technical Committee, Member

European Solar Thermal Industry Federation (ESTIF), Member

European Technology Platform on Renewable Heating and Cooling (RHC-platform), President

Fachinstitut Gebäude-Klima (FGK), Member

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FitLicht – Fördergemeinschaft innovative Tageslichtnutzung, Member

Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW) e. V.
- *Arbeitskreis "Photovoltaik",Co-operating Member*
- *Arbeitsgruppe "Oberschwingungen", Co-operating Member*

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Fraunhofer-Allianz Nanotechnologie, Member

Fraunhofer-Allianz Optic Surfaces, Member

Fraunhofer-Allianz Photokatalyse, Member

Fraunhofer-Allianz SysWasser, Member

Fraunhofer-Netzwerk Batterien, Member

Fraunhofer-Netzwerk Elektrochemie, Member

Fraunhofer-Netzwerk Energiespeichersysteme und Netze, Member

Fraunhofer-Netzwerk Intelligente Energienetze, Co-ordination

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Fraunhofer-Netzwerk Windenergie, Member

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Fraunhofer-Themenverbund Werkstoffe und Bauteile, Member

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Gesellschaft für Umweltsimulation (GUS)
- *Arbeitskreis "Batterieprüfung", Member*

Global Village Energy Partnership (GVEP), Member

International Advisory Committee of EUPVSEC, Member

International Advisory Committee of SIMC, Member

International Commission on Glass
- *TC10 "Optical Properties and Characterization of Glass", Member*

International Commission on Illumination CIE
- *TC 3-39 "Discomfort Glare from Daylight in Buildings", Member*
- *TC 3-47 "Climate-Based Daylight Modelling", Member*

International Electrotechnical Commission IEC
- *TC82 "Solar Photovoltaic Energy Systems", WG3 + WG7, Member*
- *TC105 "Fuel Cell Technologies", WG 7/WG 11, Member*

International Energy Agency IEA, Member:
Heat Pump Programme HPP
- *Annex 32 "Economical Heating and Cooling Systems for Low Energy Houses"*
- *Annex 34 "Thermally Driven Heat Pumps for Heating and Cooling"*

Photovoltaic Power Systems Program (PVPS)
- *Task 11 "PV Hybrid Systems within Mini-grids"*

Solar Heating & Cooling Programme SHC
- *Task 37 "Advanced Housing Renovation with Solar and Conservation"*
- *Task 38 "Solar Air-Conditioning and Refrigeration"*
- *Task 39 "Polymeric Materials for Solar Thermal Applications"*
- *Task 43 "Solar Rating and Certification Procedure – Advanced Solar Thermal Testing and Characterization for Certification of Collectors and Systems"*
- *Task 44 "Solar and Heat Pump Systems – Systems Using Solar Thermal Energy in Combination with Heat Pumps"*
- *Task 48 "Quality Assurance and Support Measures for Solar Cooling"*
- *Task 49 "Solar Process Heat for Production and Advanced Applications"*

International Programme Committee of GADEST, Member

International Science Panel on Renewable Energies (ISPRE), Secretariat

International Standardization Organization ISO
- *TC180 Solar Energy, WG 2, WG 5, Member*

Intersolar North America, Programme Committee Chair

Kompetenzfeld Photovoltaik NRW, Member

Kompetenznetzwerk Brennstoffzelle NRW, Member

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Monitoring and Evaluation Working Group (M&EED) by Global Village Energy Partnership (GVEP) and European Union Energy Initiative (EUEI), Member

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Solar Keymark Network, Member

Solar Power and Chemical Energy Systems SOLARPACES
- *Task I "Solar Thermal Electric Systems"*
- *Task III "Solar Technology and Advanced Applications"*

SEMI International, Board of Directors, Member

SEMI Standards, Photovoltaic Equipment Interface Specification Task Force (PV-EIS), Member

Solar Energy Research Institute of Singapore (SERIS), Advisory Board

Stiftung Solarenergie, Advisory Board

Symposium Photovoltaische Solarenergie, OTTI Technologie-Kolleg, Scientific Advisory Board

Symposium Thermische Solarenergie, OTTI Technologie-Kolleg, Scientific Advisory Board

User Forum "Thin-Film Photovoltaics", Scientific Advisory Board

VDI-Gesellschaft Technische Gebäudeausrüstung
- *Richtlinienausschuss 4706 "Kriterien für das Innenraumklima"*
- *Richtlinienausschuss 4650, Blatt 1 und Blatt 2 "Wärmepumpen"*
- *Richtlinienausschuss 4645, "Planung und Dimensionierung von Wärmepumpen von Heizungsanlagen mit Wärmepumpen in Ein- und Mehrfamilienhäusern"*
- *Richtlinienausschuss 2164 "Latentspeichersysteme"*

VDMA – The German Engineering Federation
- *Productronics Association, Member*
- *Deutsches Flachdisplay-Forum (DFF), Member*
- *Organic Electronics Association (OE-A), Member*

VDMA Brennstoffzellen

- *Arbeitskreis "Industrienetze", Member*
- *Arbeitskreis "Industriepolitik", Member*

Verband der Materialprüfämter e. V. (VMPA)

- *Sektorgruppe "Türen, Fenster und Glasprodukte", Member*

Verband zu Energieeffizienz in Gebäuden, Founding Member

Verein Deutscher Ingenieure (VDI)

VDI-Gesellschaft Energietechnik

- *Fachausschuss "Regenerative Energien" (VDI-FA-RE), Member*

Weiterbildungszentrum WBZU "Brennstoffzelle", Board of Directors

Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW,
Board of Trustees

TRADE FAIRS

BAU
Munich, Germany,17.–22.1.2011

7th International Hydrogen & Fuel Cell Expo, FC Expo
Tokyo, Japan, 2.–4.3.2011

26th Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, Germany, 2.–4.3.2011

Battery Expo Japan
Tokyo, Japan, 2.-4.3.2011

Hannover Messe
Hanover, Germany, 4.–8.4.2011

21rst Symposium Thermische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 11.–13.5.2011

Intersolar
Munich, Germany, 8.–10.6.2011

Intersolar/Sonderschau PV Energy World
Munich, Germany, 8.–10.6.2011

Intersolar North America
San Francisco, CA, USA, 12.–14.7.2011

26th European Photovoltaic Solar Energy Conference and Exhibition
Hamburg, Germany, 5.–8.9.2011

CLEAN TECH MEDIA AWARD
Hamburg, Germany, 16.9.2011

f-cell Forum
Stuttgart, Germany, 26./27.9.2011

Les Rendez-Vous CARNOT 2011
Lyon, France, 12./13.10.2011

UrbanTec – Smart Technologies for Better Cities
Cologne, Germany, 24.–26.10.2011

Intersolar India
Mumbai, India, 14.–17.12.2011

PUBLICATIONS

Andreas, W.; Christoph, B.; Sebastian, M.; Marc, H.; Pierre, S.-C.; Daniel, B.
»Impact of Thin Intermediate Thermal Oxide Films on the Properties of PECVD Passivation Layer Systems«, in: Proceedings, 37th IEEE PVSC 2011, Seattle, WA, USA, 19.–24.6.2011

Baur, C. (European Science and Technology Centre, Noordwijk, The Netherlands); Siefer, G.; Kern, R.; Winter, S. (Physikalisch-Technische Bundesanstalt, Braunscheig, Germany)
»Primary Solar Cell Standards – Comparison of Extraterrestrial Synhetic Calibration«, in: Proceedings, 9th European Space Power Conference 2011, Saint-Raphael, France, 6.–10.6.2011

Benoit, P.; Bloch, A.; Kohrs, R.; Wittwer, C.
»Charge Application Protocol for Different Bidirectional Integration Topologies«, in: Proceedings, Smart Grids and E-Mobility 2011, Munich, Germany, 17./18.10.2011, CD-ROM

Bett, A. W.
»III-V Multi-Junction Solar Cells and Concentrating Optics – A Perfect Match for Highest Efficiencies«, in: Photonics in Germany

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»Printed Contact on Emitter with Low Dopant Surface Concentration«, in: Proceedings, 3rd Workshop on Metallization for Crystalline Silicon Solar Cells 2011, Charleroi, Belgium, 25.11.2011

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