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FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2010

Cover:
A view into the saw-toothed roof construction of the atrium in the main building of Fraunhofer ISE. The photovoltaic modules integrated there are installed within the double glazed units. In addition to providing thermal insulation in winter, they also serve as sun-shading elements in summer. With the new premises of Fraunhofer ISE (2001) a building was constructed which sets standards in combining architecture and solar technology, according to the motto „Exemplary building with the sun". High-quality working conditions and efficient use of energy, naturally with integrated solar systems, were the common goals of the building owners, the architects, Dissing+Weitling from Copenhagen, the engineering company, Rentschler & Riedesser from Stuttgart and the planning experts from Fraunhofer ISE.

FOREWORD

2009 was designated as the Year of Energy by the German Federal Ministry of Education and Research (BMBF), and this year's topic "The Future of Energy" appeared as a recurring theme throughout the calendar of public events. As a contribution, the Fraunhofer Institute for Solar Energy Systems ISE together with the Fraunhofer Energy Alliance organised the Fraunhofer Energy Days on 23–24 September 2010 in Berlin. Around 200 speakers and guests, including Prof. Klaus Töpfer, the former German Environment Minister and currently Executive Director of the Institute for Advanced Sustainability Studies, participated in the event with contributions and discussions focusing on the "Energy Concept for Germany – With New Energy." The Fraunhofer Energy Days showed that the Fraunhofer-Gesellschaft with its Fraunhofer Energy Alliance, a union which combines the energy expertise of the participating Institutes within the Fraunhofer-Gesellschaft, holds a leading position in Germany in the field of renewable energy and energy efficient technologies.

Renewable energy also defined the 2010 political agenda in Germany, however the outcome was not always positive. The federal government did define an energy program containing ambitious targets, however, extending the operating life of nuclear power plants has consequences: Due to overproduction, the electricity generated by renewable energy sources can not be completely fed into the grid. In addition, it is to be feared that in the upcoming 2011 revision of the Renewable Energies Act (EEG), special interest groups will attempt to slow down the development of photovoltaics.

Supported by its staff position Energy Policy and its membership in the ForschungsVerbund Erneuerbare Energien (FVEE), Fraunhofer ISE cooperated on a study and resulting benchmark paper on a German electricity supply using 100 percent renewable energy by 2050. In mid-year this study was presented to the German Federal Environment Minister Dr. Norbert Röttgen. Fraunhofer ISE also worked with the FVEE to make recommendations for the German federal energy research program. Commissioned by the Federal Environment Ministry, Fraunhofer ISE is coordinating a study on the development of an integrated heating and cooling strategy for Germany. Using scenarios which consider federal government measures, the future development of the heating and cooling market in Germany is extrapolated. The aims are to accelerate the reduction in energy consumption and to increase the fraction supplied by renewable sources.

On the international arena, the ramifications of climate change and the urgently needed energy transformation were the key points of focus. In the Mexican city of Cancún, participants of the international UN climate conference surprisingly agreed on a compromise. Further, the Fraunhofer-Gesellschaft joined the Destertec Industrial Initiative, whose goal is to promote an international electricity grid for solar and wind energy. The changeover to more efficient energy use with an increasingly larger fraction of renewable energies presents us with a huge global economic stimulus package that will create many new jobs. In 2010 in Germany alone, almost an entire percentage point of the gross domestic product can be attributed to renewable energies.

In 2010 the positive financial and staff development continued at Fraunhofer ISE. The annual budget increased 12 percent to more than 53 million euro (61 million euro including investments). The number of employees grew to over 1000. International comparisons show us in an excellent position. To continue our growth in the future as the largest solar energy research institute in Europe, we undertook the following steps to lead the way:

In 2010 we held the ground-breaking ceremony for our new laboratory building and we celebrated our one thousandth employee on the same occasion. In the near proximity of our main building in Freiburg, a laboratory building with over

4000 m² will be built. In this facility, a 2000 m² laboratory and testing area for the Material Research and Coatings Group as well as Microstructure Surfaces Group will be located. The federal and state governments are equally splitting the costs of the new laboratory building at 10.2 million euro, which was a part of my appointment funds. At this time, we would like to again express our appreciation.

In further adapting our structure to the tasks of the future, we have created two new departments for topics that have been researched at Fraunhofer ISE for a long time now: solar thermal systems and module technology. The Department of Solar Thermal Systems and Optics will be headed by Dr Werner Platzer and the Department of Photovoltaic Modules, Systems and Reliability by Dr Harry Wirth.

Again in 2010, the scientific results from our researchers were distinguished with many prizes and honours (see page 12):

This year one particular research team at Fraunhofer ISE received multiple prizes. The III-V Solar Cells and Epitaxy Group, which had reached a world record efficiency of 41.1 percent with its multi-junction solar cell in 2009, was honoured nationally and internationally by several institutes. Leading the way were Dr Andreas Bett and Dr Frank Dimroth. With their group they received the Joseph von Fraunhofer Prize, the highest award bestowed by the Fraunhofer-Gesellschaft and awarded to Fraunhofer ISE for the first time. We are especially proud of the prize from the Fondation Louis D. At 750.000 euro this is the highest-endowed scientific prize in France. In June 2010, it was awarded to Dr Frank Dimroth at a ceremonial event at the Institut de France in Paris. In Brussels the research results in concentrating photovoltaics were distinguished with the EARTO Innovation Prize. Dr Hans-Martin Henning was offered a professorship at the Hochschule für Technik, Stuttgart in the Department of Architecture in the field of Climate Engineering, which he declined. In this context, I would like to mention the recipients of the 2011 Benefits for Excellence from the Fraunhofer-Gesellschaft: Dr Dietmar Gerteisen, Dr Thomas Schlegl, Gerhard Stryi-Hipp and Dr Wilhelm Warta.

In 2010 we celebrated not only numerous awards but also an anniversary, the start of co-operations and the inauguration of several new laboratory facilities:

In North Rhine-Westfalia our Laboratory and Service Center Gelsenkirchen celebrated ten years of operation. We set up this site in 2000 with the support of the regional government in North Rhine-Westfalia. The goal was to establish exemplary conditions for performing research at near industrial standards and close to the customer. After ten successful years, we celebrated this occasion on 5 November 2010 with the Center's director Dr Dietmar Borchert. At this event a new 400 m² technology laboratory for silicon heterojunction solar cells and silicon thin film solar cells was inaugurated. In Northern Germany a festive event took place to inaugurate the close co-operation with the company Dispatch Energy. Located in Itzehoe, the company developed a complete battery system together with the Fraunhofer ISE and ISIT. The system enables decentrally produced solar power to be stored temporarily and used at the source at economically feasible rates. On the same day several hundred kilometres to the south, the inauguration of the Energy Park Dürbheim took place. Here a 5 megawatt photovoltaic system was put into operation. Fraunhofer ISE will perform the monitoring and carry out research in the area of large inverters and grid integration.

Together with the Fraunhofer Center for Sustainable Energy Systems CSE, Boston as well as the VDE Institute and the Canadian Standards Association (CSA) group, we laid the foundation stone for a new international test and accredi-

tation laboratory for photovoltaic modules in Albuquerque, New Mexico, one of the sunniest locations in the USA. The so-called CFV Solar Test Laboratory supplements the already existing joint venture locations of Freiburg and Singapore, the latter in cooperation with the Solar Energy Research Institute of Singapore SERIS. With all three facilities, we contribute to the quality assurance of PV modules.

For our research work in the group of High-Efficiency Silicon Solar Cells – Characterisation and Simulation on location in Freiburg, we added a 450 m² technology hall called ETAlab. The areas of focus are solar cell calibration and novel laser and metallisation processes. Further, in our new megawatt laboratory, we can operate and perform measurements on inverters with up to 1.25 megawatts of power. The new power electronics laboratory enables highly precise inverter measurements as well as all tests prescribed by the new mid-voltage guidelines. In the Smart Energy Lab, Fraunhofer ISE offers an ideal platform for the development and evaluation of energy management solutions. The laboratory is equipped to analyse, evaluate and develop Smart Home and Smart Grid technologies. In the area of fuel cell development, we could finalise the development work on our 50-channel impedence spectroscopy system. With this world-wide unique system, spatially resolved measurements are performed to analyse electrochemical reactions, transport processes, charge carrier and thermal distributions. The measurement results can be compared with simulations.

In addition to the Fraunhofer Energy Days, we hosted the Solar Summits in Freiburg for the third time in a row. The conference series took place from 13–15 October 2010 in the Konzerthaus in Freiburg. The topic of focus this year was sustainable mobility based on electricity generated from renewable sources, hydrogen and on the use and potential of biofuels. The Solar Summit 2011 will focus on organic

1 *Prof Dr Eicke R. Weber welcomes Dorika Fleissner as 1000th employee at Fraunhofer ISE.*

2 *Ground-breaking ceremony for the new laboratory building: Prof Dr Hans-Jochen Schiewer, Rector of the Albert Ludwig University, Freiburg; Ministerial Director Dr Dietrich Nelle, Director of the Subdivision Research Organization, German Federal Ministry for Education and Research; Prof Dr Eicke R. Weber, Director Fraunhofer ISE; Ministerial Director Klaus Tappeser, Office Head in the Ministry of Science Baden-Wuerttemberg; Otto Neideck, First Mayor of the City of Freiburg; Veronika Reisser and Georg Brechensbauer, both BMBW Architects BDA + Partner; Markus Scheben, Department Head for Building Affairs and Estates, Fraunhofer-Gesellschaft (from left to right).*

electronics and photovoltaics. For the first time, a new conference series SiliconPV – International Conference on Silicon Photovoltaics will take place from 17–20 April 2011 in Freiburg. We are looking forward to the opening ceremony of the new conference series on the topic "Advanced Cell and Module Concepts" and are pleased to be able to welcome numerous prestigious representatives from science and industry to the event in Freiburg.

To conclude, I would like to sincerely thank 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 and especially our project partners in industry. Your continuous support and sustained co-operation is a special honour and motivation for us also in 2011 to commit our efforts towards 100 percent renewable energy.

Eicke Weber

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Andreas Bett Gerhard Willeke Karin Schneider Gerhard Stryi-Hipp Ralf Preu Stefan Glunz Thomas Schlegl

ORGANISATIONAL STRUCTURE

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

Hans-Martin Henning Harry Wirth Eicke R. Weber Christopher Hebling Günther Ebert Werner Platzer Holger Schroeter

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THE INSTITUTE IN BRIEF

Institute Profile

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, alternative photovoltaic technology, renewable power generation 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" 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 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), was founded in 2000. It 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 provides training sessions on characterisation procedures and solar cell technology as well. In 2010 the facility celebrated its tenth anniversary. On this occasion a new laboratory for large-area silicon heterojunction solar cells and silicon thin film solar cells was inaugurated (see report p. 74).

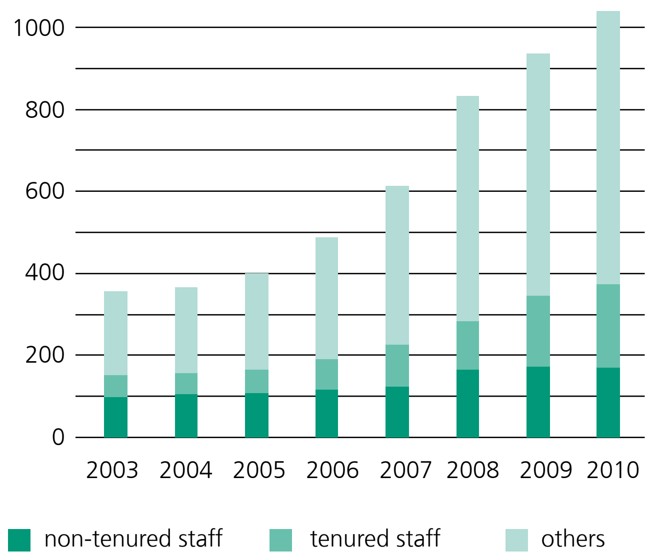
The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle/Saale was jointly founded in 2007 by the Fraunhofer Institute for Mechanics of Materials IWM, Freiburg and Halle, and the Fraunhofer ISE. Fraunhofer IWM contributes its expertise in the area of optimisation and evaluating silicon process technologies and module integration. Fraunhofer ISE's competence lies in the manufacture of materials, solar cell and module development as well as characterisation (see report p. 58). The central facilities are presently Reliability and Technologies for Grid Parity (CSP-ZTN) and the Laboratory for Crystallisation Technology (CSP-LKT). On 1 October 2010, the foundation stone was laid for Fraunhofer CSP's new building.

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 was founded in 2008. At Fraunhofer CSE, the expertise and technology in the field of renewable energy that is already established in Europe is to be further adapted and introduced 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. Further information about Fraunhofer CSE can be found on page 10.

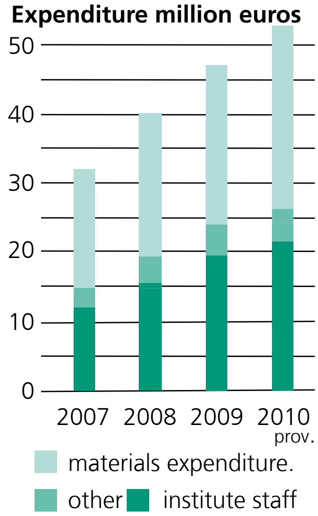
The financial structure of the Fraunhofer-Gesellschaft distinguishes between the operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. In 2010 our operational budget totalled 53.2 million euro. In addition to the expenditure documented in the graph, the Institute made investments of 8.4 million euro in 2010 (not including investments for building construction and the economic stimulus programme).

Personnel

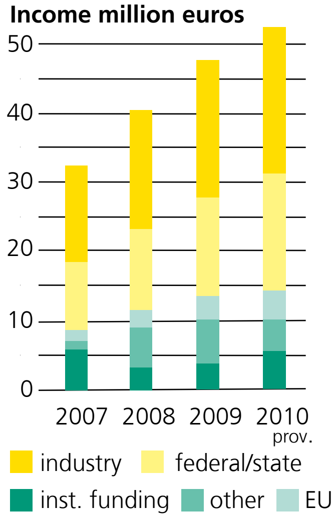


On 31 December 2010, a total of 1041 staff members were employed at Fraunhofer ISE. Included in this total are 128 doctoral candidates, 127 diploma/masters students, 42 trainees, 8 apprentices and 257 scientific assistants as well as 104 further staff (e.g., guest scientists). They provide considerable support in the research project 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.

Expenditure million euros



Income million euros



FRAUNHOFER CSE

www.cse.fraunhofer.org

1 *Fraunhofer CSE, Boston was founded in 2008 and cooperates closely with the Massachusetts Institute of Technology MIT.*

2 *Fraunhofer CSE carries out quality assurance tests for photovoltaic modules.*

The Fraunhofer Center for Sustainable Energy Systems CSE in Boston, Massachusetts has its origins at Fraunhofer ISE and the close working relationship continues. The financial partners of the Fraunhofer CSE are the Commonwealth of Massachusetts, National Grid, Fraunhofer ISE and the Fraunhofer-Gesellschaft.

Currently the work at Fraunhofer CSE focuses on the following areas:

The CSE Building Energy Efficiency Group addresses energy efficiency in the building sector with particular emphasis on retrofitting existing buildings. The focus lies in complex building envelopes as well as energy efficient building services and operating technology – an area of great need in the USA. Within the United States government's Building America Program, CSE was selected to lead a consortium comprised of members from industry, residential building development and research institutes.

The CSE Photovoltaic Module Innovation Group provides services to U.S. companies that test new materials and seek to investigate and manufacture new PV module architectures. For PV module lifetime tests, two testing centres are available: one in Boston, Massachusetts and the other in Albuquerque, New Mexico.

Intelligent Power Distribution, including Smart Grids, is in the process of being set up as part of the range of services offered by CSE.

Fraunhofer CSE initiated the innovative Fraunhofer TechBridge programme. The aim of this program is to support the commercialisation of innovative ideas for clean energy technologies. The long-standing R&D expertise from Fraunhofer is made accessible to young start-up companies. At the same time, the TechBridge programme supports Fraunhofer ventures to bring Fraunhofer know-how to the U.S. market. The U.S. Department of Energy provides a sum of US$1 million to support this objective.

R&D HIGHLIGHTS

ENERGY-EFFICIENT BUILDINGS

- Building-Integrated PV (BIPV) prototypes (multifunctional BIPV glazing) developed
- Novel sorption materials, based on metal-organic scaffolding material, synthesized
- New contrast model developed to evaluate optical comfort in office work places
- Building and energy concept for Pfizer production facility designed as commissioned by Pfizer Manufacturing Germany GmbH. For the CO_2-neutral energy supply at their production facility in Freiburg, Pfizer received the Environmental Award of Baden-Württemberg 2010.

APPLIED OPTICS AND FUNCTIONAL SURFACES

- Roll-to-roll nanoimprint lithography system for texturising silicon solar cells put into operation
- Novel structures (3-D photonic crystals and hierarchic structures) generated using interference lithography.

SOLAR THERMAL SYSTEMS

- First measurements carried out on a solar collector prototype of typical market size equipped with a bio-memetic FracTherm® aluminium roll-bond absorber
- Newly developed solar collectors with static reflectors put into operation as a demonstration system for supplying process heat to a laundry.

SILICON PHOTOVOLTAICS

- Successful block crystallisation of industry standard Cz-silicon as well as UMG-Si demonstrated
- Electro-optical modelling of solar cells with photonic structures carried out
- Screen-printed back-contact solar cells with backside charge carrier collection and 20 % efficiency manufactured at PV-TEC
- Large-area passivated metallic-compound solar cells (MWT-PERC) with 18.9 % efficiency realised
- Fast procedure for estimating the efficiency potential of mc-Si wafers by pattern identification using photo-luminescence images developed
- n-type solar cell with 22.4 % efficiency using industrially feasible rear passivation (PassDop) realised
- 19.6 % efficiency for a large-area (140 cm²) n-type solar cell with printed front side contacts and Al_2O_3 surface passivation on boron-doped emitter realised
- Edge-sealed PV module (TPedge) with 20 solar cells demonstrated and first reliability tests passed successfully

ALTERNATIVE PHOTOVOLTAIC TECHNOLOGIES

- Worldwide highest fill factor of 64 % achieved for flexible organic solar cell modules
- World record efficiency achieved for GaAs solar cells: 26.4 % at 1000 W/m², 25 °C, AM1.5g and 29.1 % for 117 000 W/m², 25 °C, AM1.5d
- Monolithic multi-junction solar cells manufactured from GaInP/GaInAs-Si using wafer bonding technology

RENEWABLE POWER GENERATION

- Active bypass diode with 50 mV forward voltage developed for solar PV module
- First off-grid CPV system for water provision and purification put into operation in Egypt
- Decentralized battery storage with long lifetime developed; transfer to pilot series production initiated

HYDROGEN TECHNOLOGY

- 50-channel impedance spectroscopy system for characterising cells and stacks put into operation
- 50 kW biomass gasifier put into operation

SERVICE UNITS

- Solar simulator with six light sources put into operation at CalLab PV Cells
- Routine measurements performed on concentrator PV modules under controlled laboratory conditions at CalLab PV Modules
- CalLab PV Cells implemented highly precise method for determining the temperature dependence of solar cell parameters.

AWARDS AND PRIZES

1

Dr Frank Dimroth and his group "III-V Solar Cells and Epitaxy" were awarded the 2nd FEE Innovative Energy Award for the record efficiency of 41.1 % achieved for high efficiency multi-junction solar cells. The award was bestowed by the Fördergesellschaft Erneuerbare Energien e.V. FEE (Society for the Promotion of Renewable Energies) at a ceremony which took place in Berlin on 2 March 2010.

Prof Dr Eicke R. Weber was elected as a member of "acatech – der Deutschen Akademie der Technikwissenschaften" in April 2010.

Dr Andreas Bett and **Dr Frank Dimroth** received the Joseph von Fraunhofer Prize for their research work on high efficiency multi-junction solar cells and concentrator modules. The prize was bestowed on 19 May 2010 at the occasion of the Fraunhofer Annual Meeting in Leipzig (fig. 4).

Third place in the Hugo Geiger Prize 2010 was awarded to **Nils Brinkmann** (ISE alumnus) for his diploma thesis on the development of a novel cell concept. This prize was also bestowed on 19 May 2010 at the Fraunhofer Annual Meeting in Leipzig. The diploma thesis is entitled: "Epitaxy through Holes – Process Development and Characterisation".

Dr Frank Dimroth received the most highly endowed science award in France for his research work "Multi-junction solar cells with record efficiencies". The award was bestowed on 9 June 2010 by the Fondation Louis D at the "Institut de France" in Paris (fig. 1).

René Kellenbenz was awarded the Student Winner Award for his conference contribution at the 35th IEEE PVSC in Honolulu, Hawaii on 6 September 2010.

Dr Christof Wittwer and his group "Intelligent Energy Systems" were awarded the M2M (Machine-to-Machine) Best Practice Award for the mobile Smart Meter (mSM) developed with VW and E.ON within the BMU "Electric Mobility Fleet Trial" project. The award ceremony took place on 16 September 2010 during the M2M Summit in Cologne.

Dr Werner Platzer and his team were awarded the most highly endowed award for international energy research. On 25 September 2010, Dr Georg Schütte State Secretary at the Federal Ministry of Education and Research (BMBF) bestowed the prize at "ewerk", Potsdamer Platz, Berlin (fig. 3).

Dr Christopher Hebling received the f-cell Special Award for best speaker on 27 September 2010 at the f-cell Congress.

Dr Andreas Bett received the EARTO Innovation Prize on 27 October 2010 in Brussels for the development of highly efficient multi-junction solar cells and concentrator modules. This award distinguishes research work that benefits the society and the economy (fig. 2).

Dr Doreen Kalz received the KIT-Doktorandenpreis (KIT Prize for Doctoral Students) in the category "Earth and Environment" for her doctoral dissertation. The Prize was awarded by the Karlsruhe Institute for Technology (KIT) on 7 November 2010. The title of her dissertation is "Heating and Cooling Concepts Employing Environmental Energy and Thermo-Active Building Systems for Low-Energy Buildings".

Dr Hans-Martin Henning was offered a professorship at the Hochschule für Technik, Stuttgart in the Department of Architecture in the field of Climate Engineering. He declined the offer.

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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: 4th November 2010).

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 could become net energy suppliers, if regenerative sources of energy 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. Buildings of this type are already operating today, but up to now they are 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 on average over the year. In current discussions, 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 can 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 for operation management and control, e.g. applying load management or storage units, which minimise the negative impact on electricity grids.

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 equipment, we also support planners and architects in designing high-quality buildings. We address the topics on 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, including solar energy technology, into the building envelope 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 play a role here, as do systems for thermal activation of building components.

With regard to supplying energy, the importance of heat pumps is increasing, just as is the significance of combined heat and power generation or its extension in combined

heating, power and cooling systems. Concerning the usage of solar energy, not only solar heating of domestic hot water and solar-assisted space heating but also building-integrated photovoltaics and solar-driven air-conditioning in summer present promising applications for the future.

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 modify, 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 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 playing a growing role, specifically when grid-connected approaches are involved. 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.

The long-term durability of new materials and components is becoming increasingly important. Over the past years, we have continuously extended our competence in this field and offer services which include not only characterisation by measurements – both indoor and outdoor – but also model-based prediction of aging processes.

Within the "EnEff-Stadt" Programme, Fraunhofer ISE is developing the energy and renovation concept for the Weingarten-West quarter in Freiburg and various pilot buildings. We planned the measures concerning daylighting, building science, energy supply and thermal comfort for the high-rise apartment block in Bugginger Straße 50, which is serving as a renovation model. The future demand for heating energy will be reduced by about 80 percent due to the optimised building envelope and ventilation system with heat recovery. A 25 kWp photovoltaic system is installed on the roof of the building.

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COMPONENTS AND CONCEPTS TO USE SOLAR ENERGY IN BUILDING FAÇADES

40 % of the CO_2 emissions in the EU are caused by the building sector. The EU has reacted to this situation and set itself an ambitious goal: From 2020 onwards, new buildings should have a net zero primary energy balance and the primary energy demand of existing buildings should be reduced drastically. In order to reach this goal, the energy efficiency must be improved and the use of solar energy via the entire building envelope must be significantly increased. The objective of the EU-funded "Cost-Effective" project is to develop components and concepts which use building façades as energy-gaining surfaces.

Francesco Frontini, Sebastian Herkel, Michael Hermann, Korbinian Kramer, **Tilmann Kuhn**, Paolo Di Lauro, Christoph Maurer, Jörn Ruschenburg, Helen Rose Wilson, Hans-Martin Henning

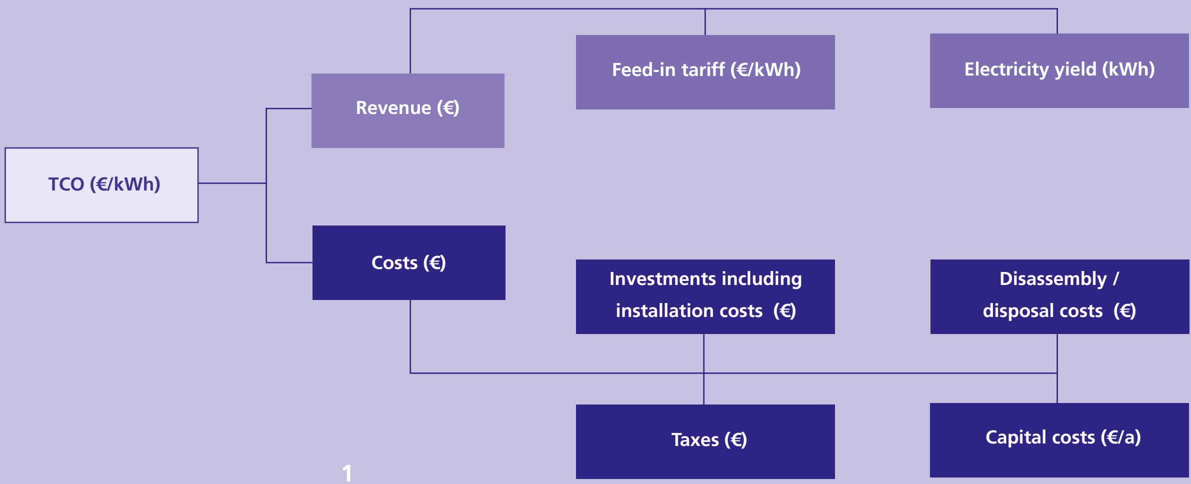
Together with the building industry, the EU has started a large and important research initiative which is intended to decrease the CO_2 emissions from the building sector significantly. The context for this initiative is provided on the one hand by the 7th Framework Programme for research in the EU and on the other by the Energy-Efficient Buildings European Initiative (E2B) within the European Construction Technology Platform (ECTP). The building industry was involved in defining the research topics of the EU calls for project proposals. The industry has contributed half of the research budget of 500 million euros.

One of the four initial projects arising from this activity is the "Cost-Effective" project, which is coordinated by Fraunhofer ISE and will run for four years with a budget of 10.7 million euros. The starting point for this project is the awareness that building façades must be used to gain enough solar energy to significantly improve the primary energy balance, particularly in taller buildings with relatively small roof areas. The project is concentrating on the renovation of existing high-rise, non-residential buildings.

1 *Evacuated tubular air-heating collector integrated into a façade.*

In a first step, categories of high-rise buildings were defined. Now, technical and economic concepts and new components for renovation are being developed within the project for the five categories with the highest CO_2 emissions. Five new multifunctional façade components will be developed by early 2011. Some prototypes have already been constructed:
- a semi-transparent, solar thermal façade collector, which is integrated into the glazing and provides solar control and glare protection simultaneously
- a solar thermal air-heating collector based on evacuated double glass tubes with good stagnation performance and high operating temperatures
- semi-transparent PV glazing with angle-selective transmittance for simultaneously optimised solar yields, solar control, glare protection and view
- a new ventilation system with central heat recovery from the exhaust air and distributed pre-heating of the inlet air integrated into the façade
- an unglazed solar collector integrated into plaster rendering and combined with a specially developed heat pump

The definition of technical concepts for the five building categories has been completed and the reports with results are available via the project web site. The four-year project will run until the end of September 2012 and is funded by the EU Commission.



BUILDING-INTEGRATED PV IN THE "SOLAR-VALLEY MITTELDEUTSCHLAND" CLUSTER

Fraunhofer ISE is coordinating the joint project entitled "PV – Building and electric system integration (BIPV)" within the "Solarvalley Mitteldeutschland" cluster of excellence that is funded by the German Federal Ministry of Education and Research (BMBF). The main goal of the project is to reduce the total cost of ownership (TCO) per kWh output electricity for entire BIPV systems. Building-related and electrotechnical expertise of Fraunhofer ISE are being combined to develop the evaluation methodology.

Daniela Dirnberger, Tilmann Kuhn, Wendelin Sprenger, Annette Trippe, **Helen Rose Wilson**, Hans-Martin Henning

In the past, PV component manufacturers have often developed their products independently of each other, without taking sufficient account of their interaction in a BIPV system (BI – "building-integrated"). However, holistic evaluation of the entire system over its complete lifetime is very important, as significant further cost reduction can be achieved by optimising the systems technology. This includes the modules, cabling, safety technology, grid connection, inverter, installation, maintenance and service as well as the building functionality.

Within the "PV – Building and electric system integration (BIPV)" project, two module manufacturers, an inverter manufacturer, a system integrator and two research institutes are working together with us to reduce the total cost of ownership for entire BIPV systems per kWh of electricity fed into the grid. In co-operation with the Karlsruhe Institute of Technology, a methodology is being developed to evaluate the economic viability based on the total cost of ownership (TCO). The methodology investigates the income and expenditure which the system owner has over the entire lifetime of a photovoltaic system. For building-integrated photovoltaics, account is taken of saved investment and operating costs which arise from the multi-functionality of the photovoltaic elements, e.g. for shading or weather-tightness of the building. As a foundation for the methodology, the TCO structure for photovoltaic systems was analysed and all relevant influences and components were presented in a tree diagram with several levels of complexity. Figure 1 shows the upper level of this tree diagram, presenting the TCO division into revenue and costs. The multi-branched tree structure formed the basis for programming a calculation tool, whereby this first version focussed on detailed treatment of the cost side. The next stage in developing the methodology is concentrating on calculating the electricity yield under the specific conditions applying to BIPV systems. For façade-integrated PV systems, obliquely incident solar radiation plays a much more important role than for tilted, south-oriented open-field systems. In TestLab Solar Façades, the existing calorimeter (for angle-dependent determination of the g value) was equipped to measure angle-dependent IV characteristics of BIPV elements. These measurements complement the electrical characterisation under standard test conditions in CalLab PV Modules. To check and validate the yield calculations, three photovoltaic and four BIPV systems in total will be monitored and analysed by Fraunhofer ISE in the course of the four-year project. Monitoring of the first system began in 2010, providing control data for comparison with the subsequent TCO-optimised systems.

1 *Upper level of the tree diagram which forms the basis for TCO analysis of PV and BIPV systems (TCO – Total Cost of Ownership).*

The project will run until 2013 and is supported by the German Federal Ministry of Education and Research (BMBF).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ENERGY-EFFICIENT RENOVATION OF AN APARTMENT BLOCK IN FREIBURG

The 16-storey apartment block in the Bugginger Strasse in Freiburg is the first building to be renovated to modern energy-saving standards in the renovation programme for the suburb of Weingarten. By optimising the building envelope and heating supply, a standard corresponding to the passive-house level has been reached for the building that dates from 1968.

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

The western part of the Freiburg suburb of Weingarten, which was built in 1960–1968, will be modernised over the period from 2007 to about 2018. The project encompasses an area of app. 30 ha, where about 5800 people live. Most of the apartments belong to the municipal building society of Freiburg, the Freiburger Stadtbau GmbH. The project objectives are to plan, implement and analyse measurements of the energy-relevant renovation of the buildings and energy supply in this suburb. The aim is to reduce the primary energy consumption for all energy services by 50 % compared to the current situation and to present a model for energy-relevant town renovation for future emulation. The project intends to pave the way for sustainable, CO_2-neutral energy supplies.

As part of the modernisation measures, it was decided to renovate one of four identically constructed apartment blocks as an example. Before renovation, the building had a living area of app. 7300 m². 90 single-bedroom and two-bedroom flats with floor areas of 60 and 80 m² are distributed over 16 storeys. Due to the compact building construction, the heating energy consumption of 70 kWh/(m² a) is relatively low for a building of this period. The renovation goal is to reduce the heating energy demand by about 80 % to 15 kWh/(m² a). The primary energy consumption for heating, domestic hot water, auxiliary energy and household electricity is not to exceed 120 kWh/(m² a) after renovation. To achieve this, the energy performance of the entire building envelope is being optimised with well-known measures such as effective thermal insulation of the façade, roof and basement ceiling, and installation of triple glazing. A central ventilation system with heat recovery is planned to reduce the ventilation heat losses. The existing building construction with structural concrete panels and projecting concrete floors as balconies demands a detailed analysis of thermal bridges. One essential measure is to integrate the existing balconies into the thermal building envelope and to add new balconies which are thermally separated from the façade. The gain in living area allows the floor plans of the apartments, which are too large for modern requirements, to be redesigned. While the number of rooms remains unchanged, the new apartments have a living area from 50 to 75 m². The total living area is thus increased to app. 8200 m² for a total of 135 apartments. Lighting and thermal simulations of the new apartments were made to investigate their lighting situation and thermal comfort and then to derive the specifications for the façade planning (window position, window-to-wall ratio and glazing quality). The goals for the heating energy and primary energy demands have been met in the planning phase. After completion of the renovation, the real building operation will be monitored with extensive measurements to obtain exact data for the consumption.

1 *Renovated façade with 200 mm thick integrated thermal insulation, triple glazed windows and thermal separation of the new balconies.*

2 *To reduce thermal bridges, aerogel insulating mats with a thermal conductivity of 0.013 W/(mK) have been installed.*

The project is supported by the German Federal Ministry of Education and Research (BMBF) as part of the "EnEff:Stadt" programme.

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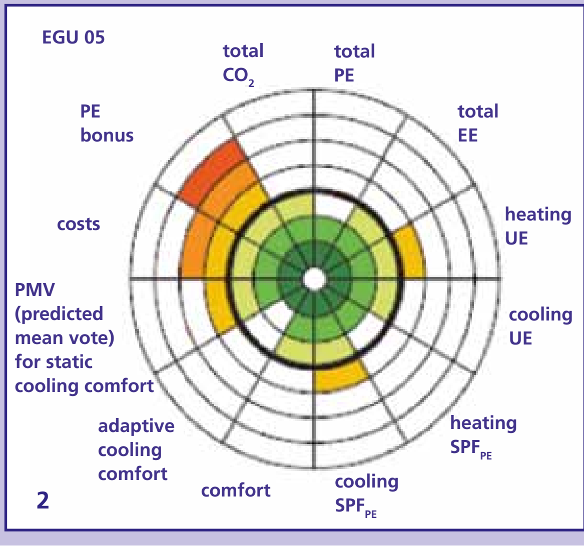

EXERGY MONITORING FOR BUILDINGS USING AMBIENT ENERGY FROM THE GROUND

Thermo-active building systems (TABS) have become established as heating and cooling systems for low-energy office buildings. Ground-connected heat pumps with reversible operation supply energy efficiently for these systems throughout the year. A cross-sectional analysis demonstrated high energy efficiency for these supply systems and indicated potential to optimise the thermo-hydraulic design and system operation.

Martin Fischer, Sebastian Herkel, Dirk Jacob, Doreen Kalz, **Jens Pfafferott**, Nicolas Réhault, Sebastian Zehnle, Hans-Martin Henning

Five buildings using ambient energy from the ground are being measured and analysed in cooperation with industrial and research partners. New control algorithms and operation management strategies are developed on the basis of coupled building and system simulations. Experience gained from operation is integrated into quality assurance procedures. The focus is on optimising the interaction between the supply, distribution and release of heating and cooling energy. Heating and cooling concepts with ambient energy achieve seasonal performance factors (SPF) between 3 and 3.8 kWh_{heat}/kWh_{el} for the heating mode (for the heat pump plus primary pump). If the ground is used directly for cooling, the SPF for the cooling mode is between 7 and 14 $kWh_{cooling}/kWh_{el}$ (only the primary pump for the earth probes or groundwater reservoirs). A reversible heat pump achieves an SPF of 5.8 $kWh_{cooling}/kWh_{el}$ for the chiller plus primary pump during combined operation of direct and mechanical cooling. The auxiliary electricity consumption for the pumps in the primary and the secondary circuit is between 3 and 10 $kWh_{el}/m^2_{net}a$ and demonstrates that low values can really be achieved. In all projects, a ventilation system combined with the temperature-controlled surfaces ensures that the indoor climate is pleasant and the air quality is good.

1 *Heating and cooling with ambient energy operate with small temperature differences. Optimal thermo-hydraulic design and operation management of the complete system is thus essential .*

2 *Comprehensive evaluation of the "EGU 05" office building according to usable energy UE, end energy EE, primary energy PE, CO_2 emissions, costs, comfort and energy efficiency (separate seasonal performance factors – SPF – for heating and cooling).*

These heating and cooling concepts combine expertise from different trades and professions, which makes planning, optimal operation and thus the potentially high energy efficiency more difficult to achieve. Thus, the development of tools and diagnostic diagrams plays a central role for comprehensive planning. In so-called "spider-web diagrams", for example, the individual numbers from planning or operation can be presented for comparison. Strengths and weaknesses of a building and energy concept can be identified and analysed during planning or operation. The spider-web diagram (fig. 2) is designed such that all quantities corresponding to a list of specifications can be presented analogously to the well-known energy labels in categories from A to G. Green indicates proximity to the target whereas red identifies a major gap. The diagram was prepared using measured values from 2005 for the ENERGON passive building in Ulm. The office building is supplied with heat and cooling energy from district heating and a borehole heat exchanger. Beginning at the left of the diagram, it is evident that high thermal comfort is provided throughout the year. Whereas the energy efficiency (SPF) in cooling operation can still be improved, the value for heating operation is already very high today. The cooling energy demand is very low, whereas the heating energy demand can still be reduced. In total, the end and primary energy consumption (EE and PE) are very low, which is reflected in low CO_2 emission.

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

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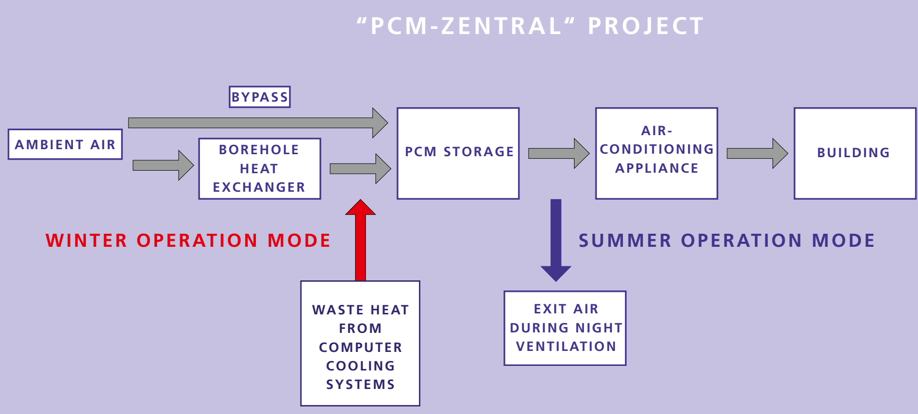

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LATENT-HEAT STORAGE UNITS IN CENTRAL VENTILATION SYSTEMS

Phase change materials (PCM) are used in different ways in buildings to temporarily store excess heat or cooling energy during the course of a day. This allows thermal comfort for users to be achieved simultaneously with lower energy consumption for air-conditioning. In the "PCM-Zentral" project, we are investigating a central PCM storage unit installed directly in the air duct, which is used both for pre-heating and pre-cooling of the inlet air.

Thomas Haussmann, Hannah Neumann, Peter Schossig, Hans-Martin Henning

A central PCM storage unit in combination with an earth-to-air heat exchanger was developed by the project partners, Emco Bau- und Klimatechnik GmbH & Co. KG, agn Niederberghaus + Partner and the Bau- und Liegenschaftsbetrieb NRW, to provide fresh air at comfortable temperatures with the lowest possible energy consumption for the new premises of the Civil and State Court in Düsseldorf. The central goal of the joint research project is to implement, evaluate and optimise the storage unit in real operation.

The choice of PCM melting point generally limits the application of a PCM in buildings to support either the heating or the cooling. However, in this concept, the PCM storage unit is used as an initial stage in adapting the temperature. A clever choice of the melting point means that the same storage unit can be used to support both heating and cooling for the first time. In addition, a 620 m long earth-to-air heat exchanger precedes the PCM storage unit, reducing the energy demand for the subsequent conventional air-conditioning units and replacing it by ambient heat and use of waste heat. To this purpose, the PCM storage unit is charged with waste heat from the central cooling system for the IT systems out of working hours, when it cannot be used otherwise. During

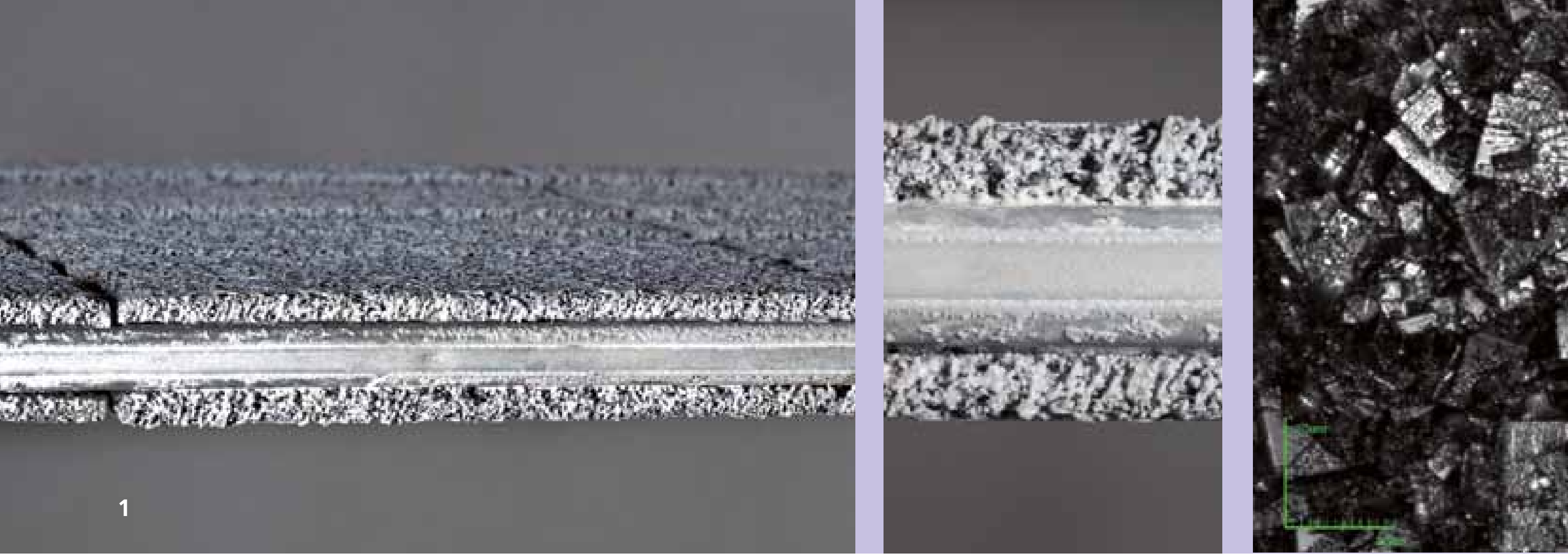
1 Opened PCM storage unit exposing the individual PCM plates installed directly in the ventilation duct.

2 The energy demand to condition the inlet air currents is reduced by the preceding earth-to-air heat exchanger and the PCM storage unit, and replaced by cooling energy from ambient heat sources.

working hours, the heat in the storage unit is used to pre-heat the inlet air. In summer, the storage unit is regenerated by flushing it with outdoor air. Depending on the outdoor temperature, the air enters via the earth-to-air heat exchanger or directly via a bypass. During the day, inlet air entering the building can be pre-cooled by the storage unit. A salt hydrate with a melting temperature of app. 24 °C is used as the PCM. Plates of extruded graphite, which serve to increase the internal thermal conductivity, are infiltrated with the salt hydrate and encapsulated within air-tight and watertight multi-layer aluminium composite films. Several thousands of these individual plates (fig. 1) are located directly in the inlet air duct before the air-conditioning units. With app. 11 tonnes of PCM, they provide a heat storage capacity of app. 500 kWh in a 15 K interval around the melting temperature. Fresh air flows through the storage unit at a rate of up to 30 000 m^3/h.

The work concentrated on selecting suitable PCM, designing the encapsulation and defining the geometrical configuration of the plates. The individual storage components were measured by the Münster University of Applied Science and Fraunhofer ISE. The central task now is to develop energy-efficient control strategies to operate the storage unit. At present, a simulation model is being prepared and validated with measured data from the monitoring project.

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



ADSORBER DEVELOPMENT FOR ADSORPTION HEAT PUMPS AND CHILLERS

Developing and constructing compact adsorption heat-transfer units is one of the most important goals of our current work on thermally driven heat pumps and chillers. Heat-transfer designs which are already applied in mass production were successfully combined with a newly developed composite of adsorbant and metal.

Gerrit Füldner, Ferdinand Schmidt, Lena Schnabel, **Daniel Sonnekalb,** Peter Schossig, **Ursula Wittstadt**, Hans-Martin Henning

As the heat which is generated during adsorption hinders the actual adsorption process, transferring the heat into the heat-transfer medium – and thus the design of the heat-transfer unit – is very important for the adsorber operation. At the same time, the largest possible amount of sorption material per volume is desirable to improve the power density of the adsorber. Our approach to solving this problem is to use porous metal substrate structures, which feature a large specific surface area and good thermal conduction properties. These form the basis of the newly developed composite material consisting of sintered aluminium fibres and zeolite. In contrast to pure sorption material, the thermal conductivity is raised significantly (to 10 instead of 0.2 W/(m K)) for a porosity of app. 30 % and a mass ratio of adsorbant to metal of 1:1.4.

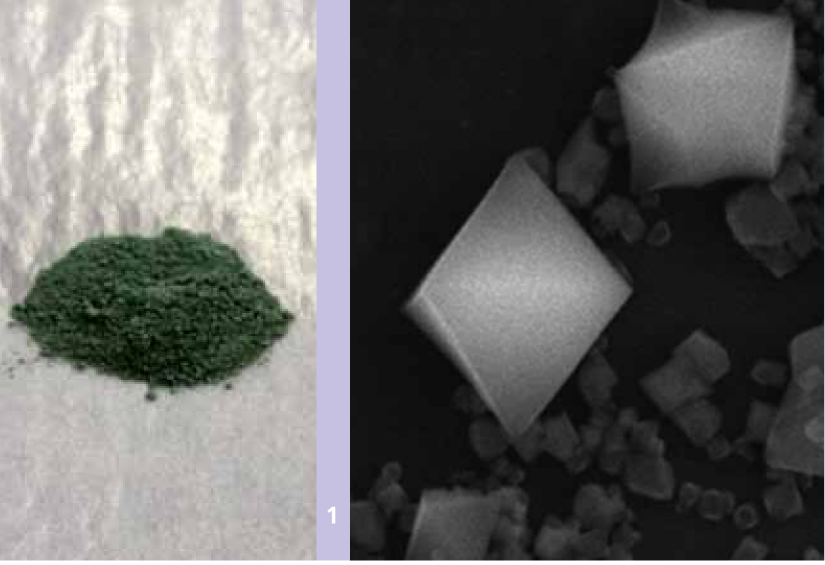
Initially, the kinetics of the adsorption process was investigated with laboratory-scale samples (30 mm x 30 mm). The sintered fibrous material was soldered onto a metal substrate sheet which represented the wall of the heat transfer unit, and then coated with sorption material (SAPO 34) by the SorTech AG company. These samples displayed rapid adsorption: 90 % of the final mass was already adsorbed after 210 s. In the next step, a prototype adsorber was produced (fig. 1). The heat-transfer structure was based on flat aluminium tubes that are used in the automobile sector. These can be coated with solder, such that all components (flat tubes, fluid header / distributor and fibrous material) can be soldered in a single step. Compared to the finned heat-transfer units currently used, the large-area contact of the composite material with the surface of the new heat-transfer unit offers the clear advantage of short pathways for heat removal.

The prototype was measured in the test rig for adsorber elements at Fraunhofer ISE. Here, the mass increase during adsorption can be measured for complete adsorption heat-transfer units while fluid flows through them. In addition, we can reproduce complete adsorption and desorption cycles experimentally.

The first measurements demonstrated a clear influence of the heat transfer by the heat-transfer fluid. When the heat removal is slow (low flow rates), the adsorbed mass increases much more slowly. No further acceleration is observed when the flow rate is increased to more than ten times the initial value, corresponding to significantly better heat extraction. Thus, the sorption side is no longer the limiting factor with the newly developed composite.

The work is being carried out as part of an internal Fraunhofer research project on “Thermally driven high-power cooling processes THOKA« (Fraunhofer IFAM, ISE, ITWM and IVV).

1 *Two details of the adsorber prototype developed at Fraunhofer ISE (left and centre) and laser microscope image of the zeolite (right).*



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NEW SORPTION MATERIALS: SYNTHESIS AND EXTENDED CHARACTERISATION

As part of the search for new sorption materials for energy-technological applications, metal organic frameworks (MOF) have been recently developed and represent a new class of materials with excellent properties. New compounds belonging to this class were identified and synthesised as part of a current research project. The measured capacity for water adsorption exceeds that for all materials that have been previously investigated. Furthermore, we were able to clearly extend the possibilities for characterisation with regard to synthesis.

Stefan K. Henninger, Philipp Hügenell, Felix Jeremias, Harry Kummer, Gunther Munz, Peter Schossig, Hans-Martin Henning

Equipment to use the adsorption process for energy-technological purposes is entering the market in the form of thermally driven heat pumps, chillers and storage units. In this context, adsorption is understood as the reversible deposition of a working medium from the gas phase on the internal surface of micro-porous solids. During this deposition, there is a phase change from the gas phase to the adsorbed phase, accompanied by the release of adsorption enthalpy. This energy can be used e.g. to heat buildings.

In addition to well known and widely investigated material classes such as zeolites and porous silica gels, further progress concerning the adsorption of water vapour has been made in recent years by synthesising zeolite-type materials such as aluminophosphates and silica aluminophosphates. In addition to modification and further development of these materials, the possibilities were extended enormously by the new class of metal organic frameworks (MOF). MOF's are distinguished by a modular structure. They characteristically consist of a central metal atom or cluster as nodes which are linked to each other by organic ligands. The innumerable possibilities for combinations of this cluster/linker concept allow diverse 3-dimensional topological configurations to be constructed and materials to be tailored to specific applications. In addition, the physical properties of the materials can be varied within wide limits to meet different technical specifications by chemical modification of the linker molecules. Among the multitude of applications for MOF, e.g. gas storage, gas separation processes, medical technology, sensors or catalysis, the application as sorption materials for thermal storage, adsorption heat pumps and chillers with water as the working fluid has been identified as being very promising.

This is also confirmed by the enormously high pore volumes and surface areas of MOF. For instance, specific surface areas of up to 5000 m^2/g and specific pore volumes of up to 2 cm^3/g were achieved. This corresponds to an increase by a factor of three or four compared to the conventionally used materials such as zeolites and silica gels.

Initial evaluation of the materials can thus be based on the pore volume and the internal surface area. To analyse the pore structure, we are equipped with a fully automatic volumetric sorption instrument. With the help of nitrogen sorption at 77 K, the internal surface area, the pore size distribution and the maximum pore volume of the synthesised samples can be determined. These physical properties are the first important parameters to assess the quality and the expected adsorption capacity of the investigated materials. In addition, this instrument is equipped to carry out adsorption measurements on other non-corrosive gases, e.g. water or methanol/ethanol.

Apart from the adsorption of water vapour as the most important characteristic, the hydrothermal stability is generally a critical point with regard to heat pumps or chillers. Due

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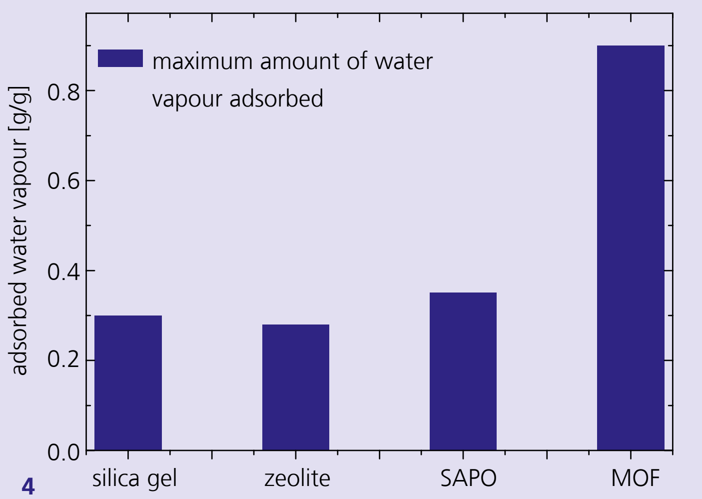

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to the organic linker, these new materials are less stable in a water vapour atmosphere than zeolites. To test this, we were able to draw on experimental facilities from another research project. Not only a specially developed cycling test system to age composites but also various different thermal balances are available for short cycling and simultaneous characterisation. For structural characterisation of the materials, we use X-ray diffraction experiments, which provide precise information on the molecular structure of the sample. Furthermore, the samples are investigated in a well-defined atmosphere (relative humidity and temperature) to identify structural changes during the adsorption process. Knowledge gained in this way can then be transferred to the next generation of materials being designed.

In addition to fundamental evaluation and identification of suitable materials, our work at Fraunhofer ISE focuses on the optimisation of synthesis routes. This step overcomes the discrepancy between the different boundary conditions prevailing for synthesis for basic research and the specifications for application in heat pumps under realistic conditions. The successful synthesis of the first materials impressively demonstrated the high potential of MOF's concerning their sorptive capacity and their chemical diversity. As well as syntheses that have been described in the literature, various modifications were made to prepare for synthesis on a larger scale. In particular, substitution of aggressive acids or the reduction of the temperature and thus the pressure were investigated. Also, the effect of tensides on the crystal morphology of the nascent compound was investigated. As an alternative to hydrothermal synthesis, microwave-induced synthesis was investigated in analogy to supersonically induced synthesis of a metal-organic network. By applying special phenomena such as local superheating, the reaction time was successfully reduced from hours to minutes. The shorter reaction time also favours the formation of smaller crystals (~2 µm). Smaller

1 *An MOF that was synthesised at Fraunhofer ISE.*
2 *The microwave reactor that is used: The time needed for synthesis was reduced significantly by microwave treatment.*
3 *Surface scan of a crystallised sample.*
4 *Comparison of the maximum amount of water vapour adsorbed by different materials and the MOF prepared at Fraunhofer ISE.*

crystals often correlate here with faster adsorption kinetics, which is advantageous for the power density in the application. Further processing of the synthesis product also plays an important role. In addition to purification with various solvents and subsequent filtration, further purification was clearly accelerated and improved by use of a centrifuge with up to 10 000 rpm.

The potential of MOF's for heat transformation applications, which had been identified on the basis of the measured pore volumes and surface areas of the synthesised materials, was impressively confirmed by water sorption measurements in our thermogravimetric equipment. The measured adsorption capacity of the produced samples clearly exceeds that of all previously investigated materials. The best sample has a water adsorption capacity of 900 g/kg and can thus additionally adsorb almost its own weight in water. An additional feature is that the adsorption occurs suddenly when a certain vapour pressure is exceeded. The only disadvantage of this unusual characteristic is that the phenomenon does not occur until the relative vapour pressure is very high ($p/p_0 = 0.5$). However, first attempts to shift the "switching pressure" have already shown success.

The work is supported by the German Federal Ministry of Economics and Technology (BMWi) and the Ministry for the Environment, Nature Conservation and Transport of the State of Baden-Württemberg.

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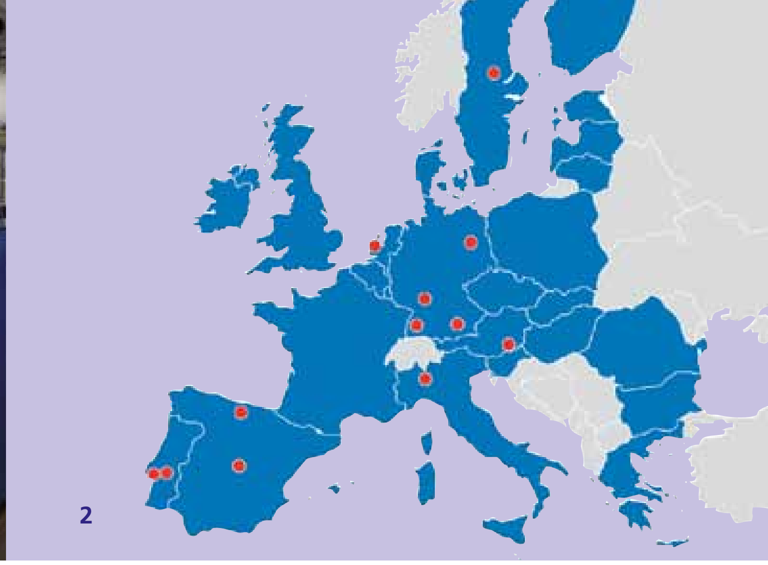

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COMBINED HEATING, COOLING AND POWER GENERATION IN THE LOW POWER RANGE

The future application of combined heating, cooling and power (CHCP) generation will be in light industrial buildings, hospitals, smaller hotels and office buildings, in which there is a need for both heating and cooling. The objective of the EU-funded "PolySMART" project was to develop the multi-facetted CHCP technology further for the low and medium power range and prepare commercially viable solutions. The four-year project focussed on the construction, operation and evaluation of twelve real systems with different specifications and different application areas.

1 *Demonstration plant for trigeneration of heat, power and cooling energy at Fraunhofer ISE. Two adsorption chillers, each with a cooling power of 5.5 kW, use the waste heat of a combined heat and power plant fuelled with natural gas.*

2 *Overview of the demonstration systems for CHCP which were installed throughout Europe and evaluated as part of the "PolySMART" project.*

Tomas Núñez, Matthias Schicktanz, **Christine Weber**, Hans-Martin Henning

Increasing numbers of combined heat and power systems are being installed and cogeneration plants in the low power range are now commercially available. They supply buildings with heat and simultaneously generate electricity which is either consumed on site or fed into the public grid. To date, this technology has been restricted to use during the heating season, as the generated heat is needed only then in the buildings. One possible solution is to allow use throughout the year and thus more efficient application: The waste heat from the so-called trigeneration plant is converted in an additional thermally driven chiller into cooling energy and used to air-condition the buildings.

In the "PolySMART" project, 32 partners from research and industry have worked on trigeneration of heat, power and cooling energy in the low and medium power range under the leadership of Fraunhofer ISE. The performance and operating data of the experimental systems were evaluated according to a procedure that was specially developed for this purpose. One of the systems was installed at Fraunhofer ISE in Freiburg and is used there to air-condition several offices with a high cooling demand. The special feature is that some of the offices are air-conditioned by ventilation coolers during the day. In the other rooms, the CHCP plant is operated during the night to discharge a cooling ceiling that contains phase change material for thermal storage. During the day, this cooling ceiling can thus accommodate cooling loads, without having to be actively cooled at the same time. This approach allows the operating time and the efficiency of the installed system to be increased.

The result of the field test is that the installed system components have achieved great technical maturity, particularly the trigeneration plants that are usually fuelled with natural gas and the thermally driven chillers with cooling power in the range from 5 to 25 kW. The most economically favourable niches for market introduction are found when the systems are used as base-load systems and complemented with peak-load generators for heating (e.g. gas-fuelled boilers) and cooling power (e.g. electric chillers). Planning and operating the combination of system components still continues to be a challenge and will need further work up to standardisation for widespread adoption to be successful.

The project was supported by the European Commission.

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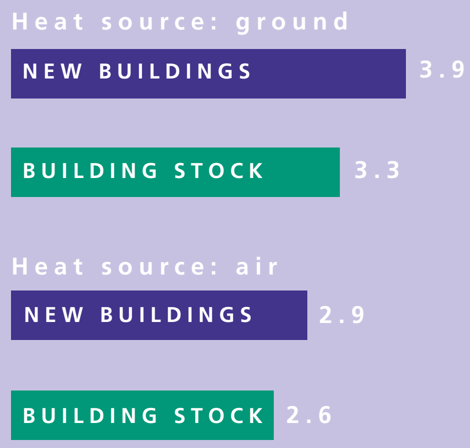


2

FIELD TEST OF HEAT PUMP SYSTEMS – ANALYSIS OF SYSTEMS IN PRACTICE

Heat pump systems are gaining increasingly large market shares for space heating and domestic hot water, both in new and renovated buildings. It is important to know the real efficiency of these systems so that they can be evaluated according to ecological, energy-relevant and economic criteria. We have thus been carrying out field tests of heat pump systems for several years now. Two broadly based field tests were completed in 2010 and a new project has started.

Danny Günther, Thomas Kramer, Thomas Lechner, **Marek Miara**, Benedikt Mayerle, Christel Russ, Jakub Wewior, Hans-Martin Henning

From 2006 to 2010, a large number of heat pumps in real applications were measured by Fraunhofer ISE as part of two projects. Data on flow rates, temperatures, heat and electricity consumption were acquired with fine temporal resolution and evaluated. We derived characteristic coefficients, the system performance and correlations to the original system specifications from the measured values.

In the "WP-Effizienz" project, about 110 heat pumps in new, free-standing houses were measured. In cooperation with seven heat pump manufacturers and the utilities, EnBW and E.ON Energie, we investigated how efficiently electric heat pumps can meet the heating demand of newly built, free-standing houses. In a further project that was financed by E.ON Energie AG, about 70 heat pumps were investigated in existing residential buildings which had not been renovated. Fraunhofer ISE controlled both the efficiency of the heat pumps used and the reliability of the heating supply to the building, and carried out an ecological and economic comparison to oil heating. Most of the investigated heat pump systems provide both space heating and domestic hot water. The seasonal performance factors were determined in both projects according to identical methodology. The electricity consumption of the heat pump itself, the brine pump or the fans and the auxiliary electric heating (e.g. immersion heater) was taken into account. The generated heat was measured directly at the outlet of the heat pump.

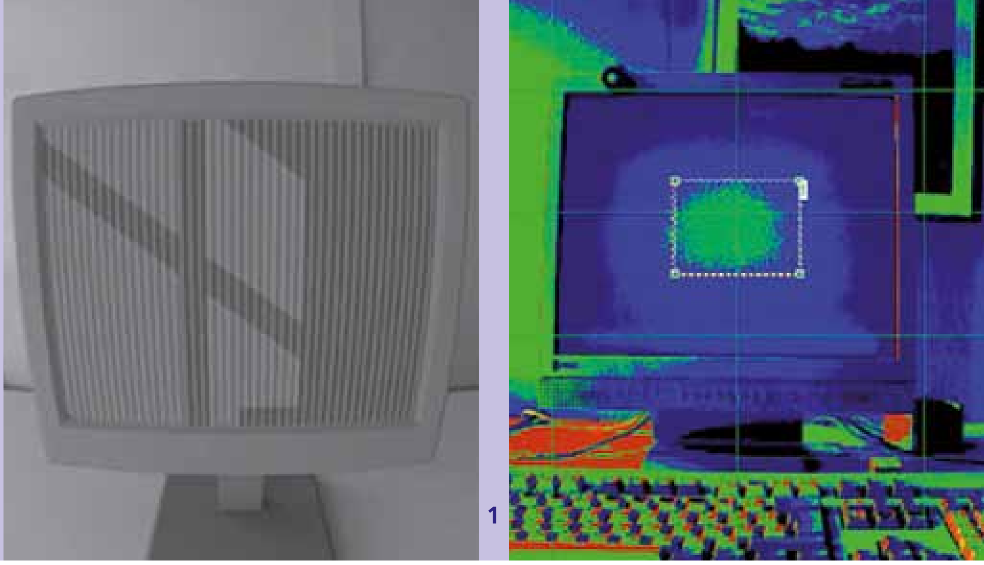
1 A technician from Fraunhofer ISE installs the measurement technology for a heat pump system.

2 Results of the field test: average seasonal performance factors for the brine/water and air/water heat pumps from the "WP-Effizienz" project (newly built) and the "WP im Gebäudebestand" project (existing buildings).

Our investigations have shown that heat pump systems are fundamentally capable of operating with an efficiency which results in ecological superiority compared to fossil-based systems. However, high efficiency is not automatically guaranteed. There are clear criteria which already play an important role for the efficiency when the heat pump system is selected, e.g. the heat source and the heat distribution system. Also the planning, installation and operation of the systems are often decisive for the efficiency which is actually achieved, and thus the ecological and economic justification for heat pump systems.

Within the "MP Monitor" project, we will now carry out a further independent and high-quality measurement of around 100 heat pumps. The essential quantities to determine the seasonal performance factors and to define the operating behaviour will be measured every minute. Commercially available heat pumps from twelve German and Austrian manufacturers will be monitored.

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



A NEW MODEL FOR OPTIMISATION OF VISUAL COMFORT IN OFFICE WORK PLACES

To achieve sustainable and energy-efficient designs and to support widespread daylight usage in office buildings, it is necessary to improve daylighting quality and visual comfort. A significant aspect of visual comfort is to avoid veiling glare on computer screens. Reflection from surrounding light sources and objects on the monitor can result in a significant contrast reduction. At Fraunhofer ISE we have developed a new method for evaluating veiling glare on visual displays which is based on contrast.

Niloofar Moghbel, Jan Wienold, Hans-Martin Henning

According to the results of one of our user assessment studies, there was no agreement between the subjective estimation of monitor quality and the existing recommendations for limiting the window luminance. This shows the necessity for another criterion to evaluate visual comfort for computer work. According to the results of the same study, veiling glare could be a good criterion for this purpose. Veiling glare occurs when the contrast ratio between foreground and background becomes lower than the minimum required contrast. Hence, to evaluate veiling glare, we first need a reliable model for the minimum required contrast. According to the latest standard (ISO/FDIS 9241–303), the minimum contrast (luminance ratio), CR_{min}, between foreground and background for performing a reading task follows the equation: $CR_{min} = 2.2 + 4.84 * L_L^{-0.65}$, in which L_L denotes low state luminance. This model is based on an experimental study in the 1940's and is far from representing today's office environment.

To our knowledge, there is no validation study to prove the reliability of this model for application to computer screens and in real office environments. For this reason, an experimental test has been developed, a user assessment study which is carried out under daylight and artificial lighting conditions. The main idea was to design an experiment which closely resembled a real visual screen-based task. This test, which is called the "RC test", is based on a reading task. We tested three age groups which included 15 test persons per group (20–30, 40–50 and 60–70), and two different window transmittance values (8 % and 54 %). The main purpose of the test was to assess how well the existing standard model for minimum required contrast correlates with the subjective results and – if necessary – to improve the model or develop a new one which fits well to the subjective results.

1 *Different illustrations of reflection on computer screens: simulated image (left) and luminance image (right).*

Evaluations of the results demonstrated a low correlation between the subjective results and the standard contrast model (the derived Pearson correlation coefficient was about 38 %). Based on the original equation, we developed a new model by adding a new variable to the model. Using this model we achieved a very high correlation with subjective results (Pearson correlation coefficient of 98 %).

The next step of our work is the development of a new computer-based method to evaluate veiling glare based on the new contrast model. This method will provide the users with a veiling glare index for any considered monitor screen under any desired lighting conditions. The tool could be applied for the following purposes with the aim of minimising veiling glare and improving visual comfort:

- improving the office layout: best location/orientation of desks, best location/orientation of monitors
- improving the façade design: shape and dimensions, transmittance
- improving the daylighting and shading system design: original design, optimisation of the control strategy

WEATHERING STUDIES OF POLYMER MATERIALS IN PV MODULES

Polymer materials are used in PV modules to protect the cells and for electric insulation. They are often exposed to extreme environmental conditions, e.g. large temperature fluctuations, UV radiation and humidity, which can adversely affect the functionality. It is thus very important to investigate the degradation processes of encapsulation materials. This provides important information for designing more realistic, faster and less expensive accelerated aging tests, which can simulate a service life of 20 years within a few months.

Philipp Hülsmann, Thomas Kaltenbach, **Michael Köhl**, Cornelia Peike, Karl-Anders Weiß, Harry Wirth

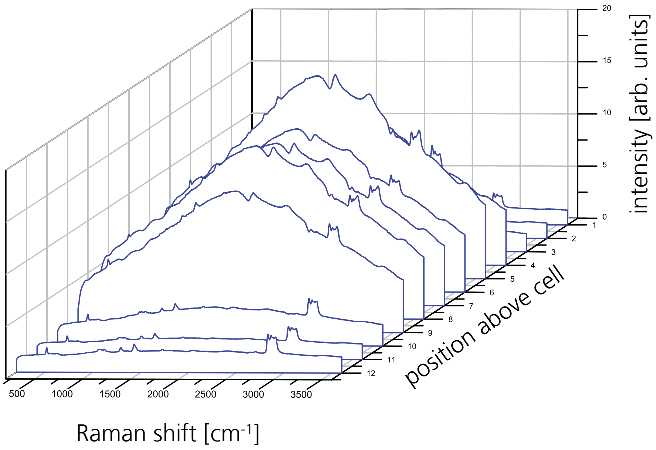
Raman spectroscopy offers an optical, non-destructive method to analyse polymers through the glass cover. Spatially resolved measurements of the ethylene vinyl acetate (EVA) encapsulation material of differently weathered photovoltaic modules detect both the differences caused by different degradation factors (humidity, UV radiation) and also inhomogeneous changes between the cell and the glazing. These are caused by diffusion processes, which initiate decomposition reactions like hydrolysis that result in fluorescent chromophores as degradation products. This leads to yellowing after further aging over decades. Around the edges of the cells, apparently other processes take place which prevent yellowing of the encapsulation material (photobleaching).

Figure 2 shows Raman spectra which were measured at equidistant (10 mm) points along a line parallel to the grid of a cell. After two years of exposure in the tropics, no change in the encapsulation can be recognised visually and the slight reduction of the output electric power is at the limit of the measurement error. By contrast, the Raman spectra for the centre of the cell clearly show the strong superimposed

1 *Outdoor exposure stand in Pozo Izquierdo (Gran Canaria).*

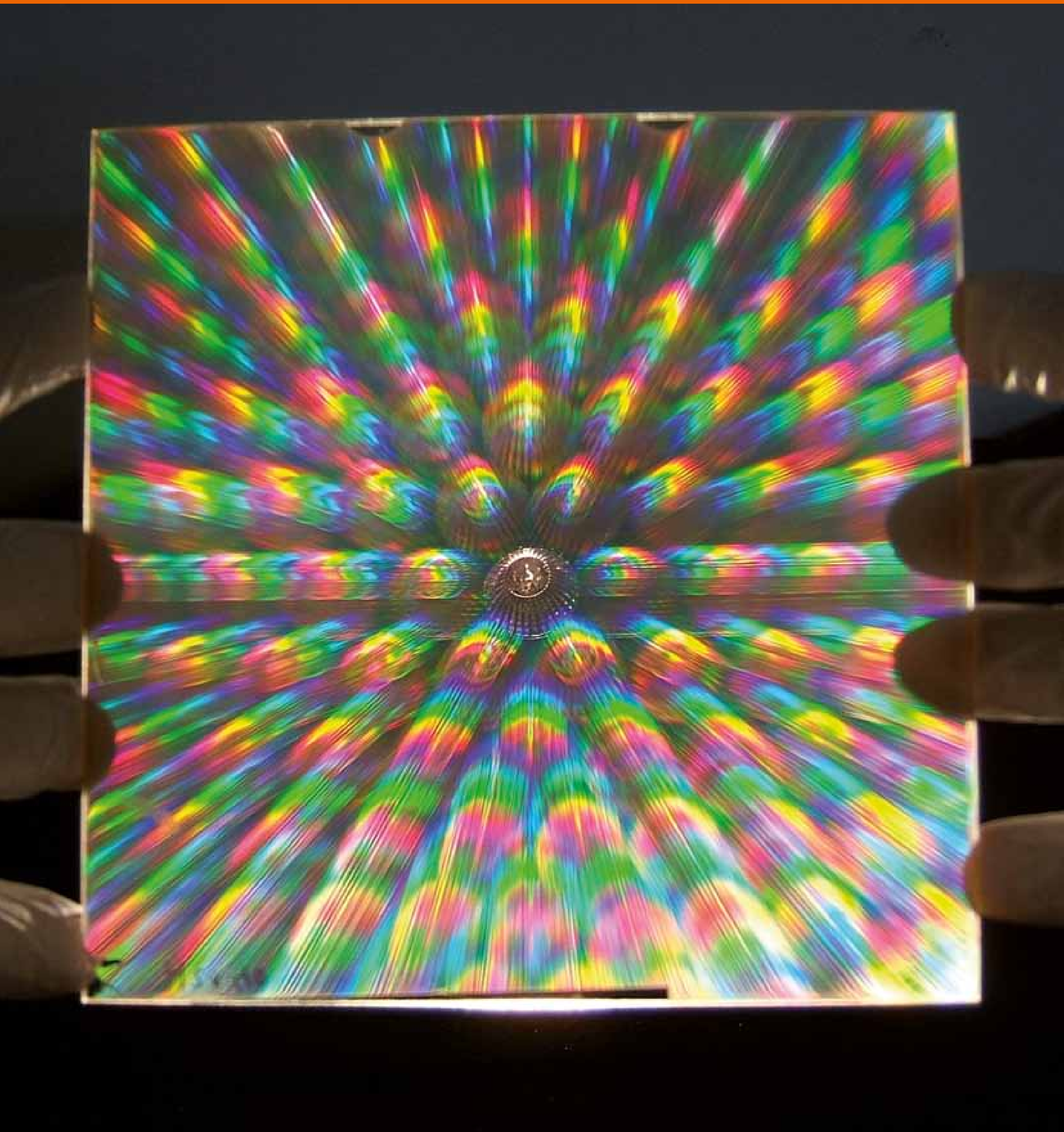
fluorescent background caused by the chromophores (degradation products). The permeation of oxygen through the rear polymer film around the cell edges resulted in oxidation of these degradation productions and the almost unperturbed EVA spectrum is visible there. The steep transition to the fluorescing region marks the position of the bus bar, which apparently acts as a diffusion barrier. Comparative measurements of identically constructed modules, which were exposed to different meteorological conditions or subjected to different types of accelerated aging, are intended to establish correlations between outdoor exposure and laboratory tests.

The cluster project on "Reliability of PV Modules 2" is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and the Schott Solar, Solarfabrik, Solarwatt, Solarworld and Solon companies.



2 *Raman spectra of the EVA encapsulation material, measured at equidistant points along a line parallel to the grid of a cell. The module had been exposed for two years in the tropics.*

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. Gasochromic glazing, in which the absorption can be adjusted over a wide range, is now technically mature and has been tested successfully in demonstration façades together with the complete associated systems technology.

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.

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

Well-defined surface textures are applied to achieve the highest efficiency values in photovoltaics. The photo shows a back-lit glass substrate covered with photoresist, which has been structured by interference lithography. This surface structure serves as the master template for producing a honeycomb structure on multicrystalline silicon by nano-imprint lithography (see article on p. 40 ff). The effect of the hexagonal structure can be recognised from the coloured diffractive image: radiation covering a wide range of wavelengths and angles is efficiently coupled in and deflected. In the solar cell, this leads to minimal reflection losses and high absorption.

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SAVING ENERGY WITH ANTI-CONDENSATION COATINGS FOR REFRIGERATION UNITS

In supermarkets, the cooling of food in refrigerated display shelves and freezers is responsible for a significant share of the electricity consumption. One obstacle to developing energy-saving refrigerated display units is the requirement that the articles should always be clearly visible to the customers. Condensation on the glass doors presented a problem up to now.

Franz Brucker, **Wolfgang Graf**, Werner Platzer

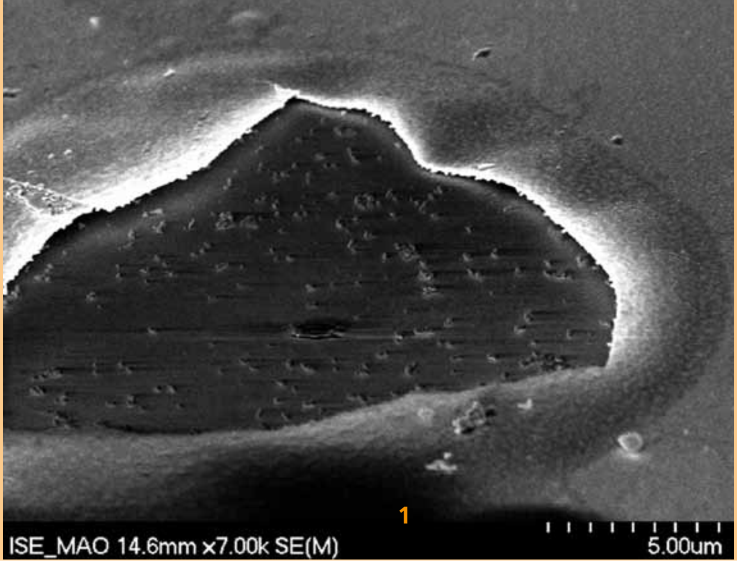
1 *View through the glass door of a refrigerated display cabinet after condensation caused by opening and closing the door. The door is divided into six sample areas with different anti-condensation coatings; area number 3 is the reference without a coating.*

In a supermarket, typically 60 % of the electricity consumption is due to cooling. A considerable share of this is caused by operating the refrigerated display cabinets and freezers. These are usually equipped with double glazed doors. The inner surface of the door is so cold that water condenses on it when it is opened. This remains on the door after it has been closed again, obstructs visibility and is thus disadvantageous for sales.

A classic solution to this problem is the application of electric heating which locally raises the dew point in the doors. However, this leads to high electricity consumption. As an alternative, numerous experimental series were devoted to developing multi-layer coatings which suppress condensation on the cold inner surface of the door without having to expend energy for heating. Different substrate layers and coating components were modified and optimised. The development represents an important step along the route toward energy-saving refrigeration units.

The main challenges were the low temperatures, well below freezing point, and mechanical loads applied by customers and staff in the supermarket. Figure 1 shows the view through the door of a refrigerated display cabinet. Six coating samples can be seen with different amounts of condensation after the door had been opened. Area number 3 is the uncoated reference, where heavy condensation is visible. By contrast, there is practically no condensation on area number 4.

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



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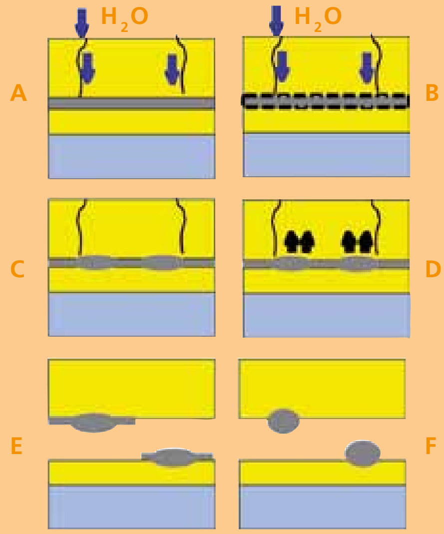


2

CORROSION MECHANISM OF LOW-E COATINGS WITH SILVER AS THE IR REFLECTOR

Low-e coatings with silver are deposited on the cavity-facing surfaces of double and triple glazing to improve the thermal insulation. With the intention of applying these low-e coatings to the outdoor surface of windows, the corrosion mechanism was investigated at Fraunhofer ISE.

Andreas Georg, Wolfgang Graf, Werner Platzer

A typical configuration of low-e coatings with silver as the IR reflective layer includes several oxide layers which increase the transmittance of the app. 10 nm thin silver layer by interference effects. Silver is classified as a noble metal. Nevertheless, the oxidation of silver at the interface to adjacent oxide layers plays a role in the corrosion of thin silver films, as was determined by comparing the corrosion with different oxide layers and various corrosive media.

The degradation of the silver layers is evident as local detachment of the encapsulating oxide layer and agglomeration of the silver. Figure 1 shows a scanning electron micrograph of a typical defect in a silver layer stack after longer periods of condensation. The continuing detachment of the encapsulation layer is visible. The remaining agglomerated silver particles appear light in the image. Under the optical microscope, usually a dust particle or similar impurity is found as the starting point for this spot corrosion. The presence of humidity is also essential for the corrosion mechanism (fig. 2). Water penetrates into the encapsulation layer (yellow)

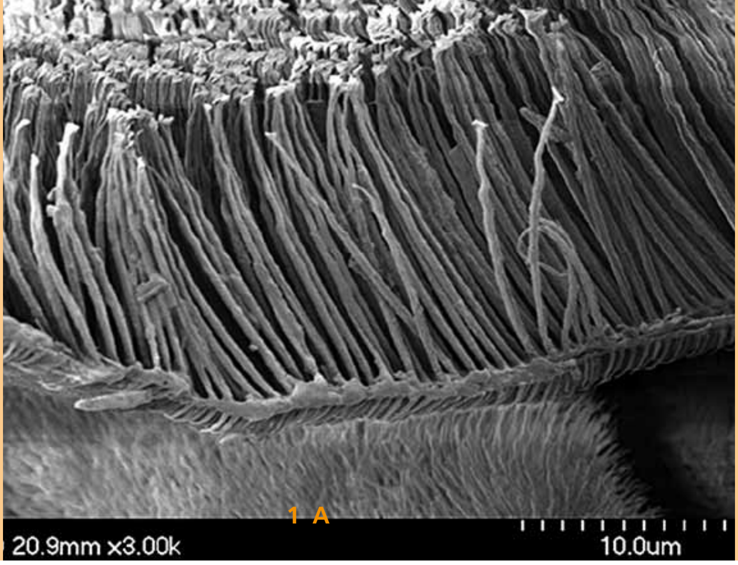
1 *Scanning electron micrograph after corrosion of a silver layer embedded between oxide layers.*

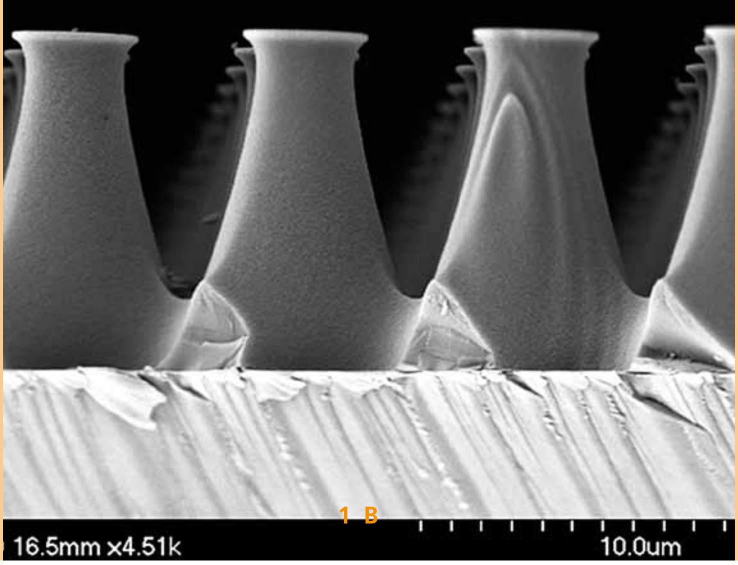
2 *Schematic representation of the corrosion mechanism in damp air for thin silver layers sandwiched between oxide layers.*

through pores or cracks and reaches the interfaces between the encapsulation and the silver (grey) layers (A). Oxygen is separated as an OH^- ion and can thus also reach the interface. At this interface, oxidation of the silver is now initiated, which reduces the surface energy (B). This is promoted by acidic media.

Silver layers already possess an intrinsic tendency toward agglomeration. For example, if silver layers are deposited without encapsulating oxide layers, they agglomerate significantly faster following corrosive attack than in the presence of encapsulating layers. Similarly, elevated temperatures favour the formation of agglomerates. By encapsulating the silver between oxide layers, the surface energy is modified such that agglomeration is opposed. This effect can be reinforced by additional adhesion layers. After the interface has been weakened, silver is able to migrate (C) and creates additional mechanical stress which can be amplified by intrinsic stress in the encapsulation layers (D). This leads to detachment of the encapsulation layer (E) and then to further agglomeration of the silver (F).

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





MICROSTRUCTURES FOR ADHESIVE SURFACES

Intrinsically adhesive surfaces which do not require applied adhesives are interesting for many applications. Their uses range from medical products, through robots, to everyday objects. Nature provides examples of such micro-structured surfaces, particularly with the gecko, which can stick to almost any surface due to the very fine hairs on the soles of its feet. We prepare surfaces corresponding to this gecko principle with our micro-structuring methods

Benedikt Bläsi, Claas Müller*, **Michael Nitsche**, Christine Wellens**, Werner Platzer

* IMTEK, University of Freiburg, ** PSE AG

Humankind has long taken nature as an example and tried to imitate its capabilities. In the "Gecko" project, we have produced structures which can stick to surfaces like the feet of a gecko. The gecko takes advantage of a microstructure on its foot soles which allow it to establish many small contact points to a surface.

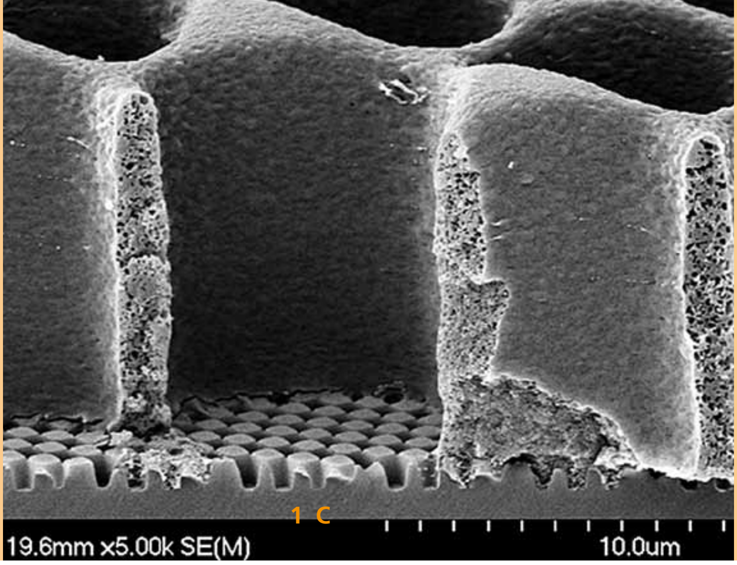
A pillar with a broadened top has proved to be a particularly effective geometrical configuration for the adhesive structures. The contact area must still remain flat. Such an undercut structure imposes special demands on the production and replication of the structures. Processes which allow such structures to be produced were developed in the course of this project.

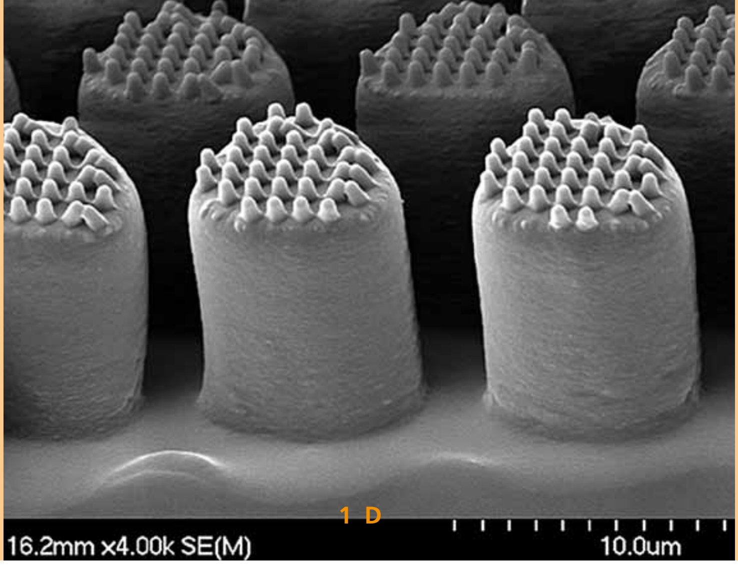
Adhesion to rough surfaces presents a particular challenge. For this purpose, the pillars must be very long and thin so that they can adapt as well as possible to the surface. Hierarchical structures offer the advantage that they combine small contact points with the required mechanical stability provided by the underlying, wider pillars. Larger aspect ratios are then possible than could be achieved without this hierarchy. In order to produce such structures, we have developed a process which allows structures with a period of one micrometre to be positioned on pillars with a diameter of eight micrometres.

Interference lithography and nano-imprint lithography are the methods we apply to produce the structures. The structures are created with interference lithography by exposure and development of a photosensitive polymer. The specific selection and processing of this material can influence the form of the feasible structures. We chose very sensitive and high-contrast materials for the large aspect ratios that are required here.

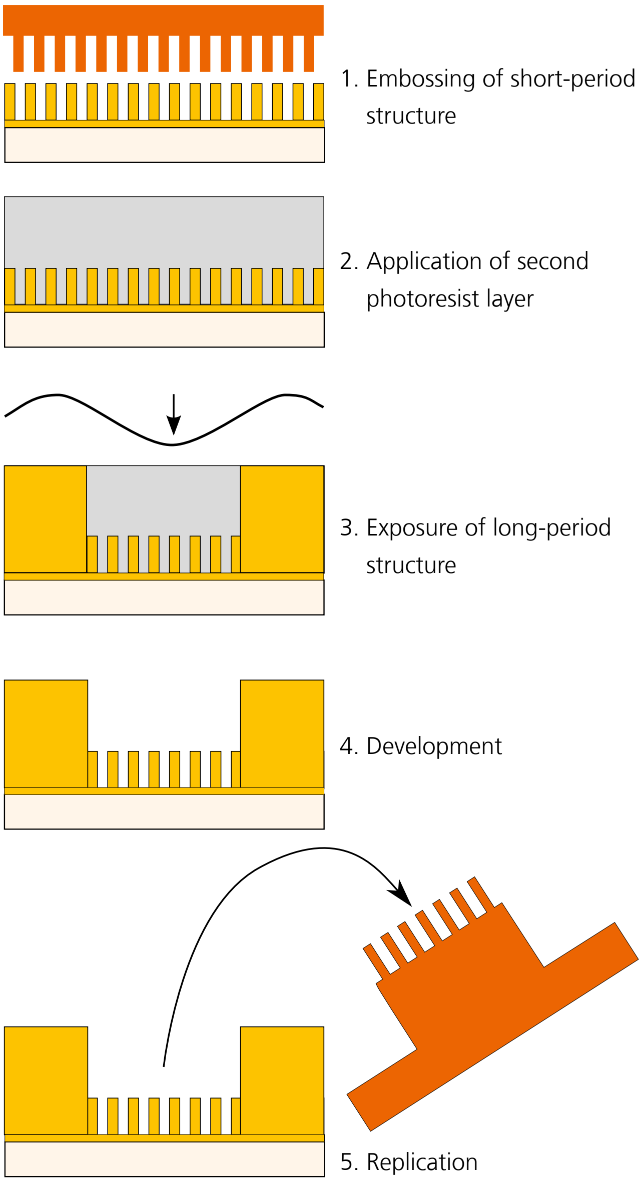
Once the master template has been produced by interference lithography, it is replicated in flexible and stiff polymers. At each replication step, the inverse profile of the embossing structure is created. A new layer of photoresist is then applied to such a replica and the second hierarchical level is exposed. The completed structure is similarly replicated in a flexible polymer. This is necessary, as the gecko effect is based on flexible materials. We have tested many materials for their compatibility and established processes with which even undercuts can be replicated.

To support the selection of materials and identification of processing parameters, a new simulation approach was developed with which the optical properties of the photoresist materials used can be taken into account better than previously. In the simulation of the exposure process, the diffraction of light on already existing structures was taken into account, which is necessary in particular for the hierarchical structures. In this way, it was possible to predict whether certain processes are feasible or not.





1 *Scanning electron micrographs:*
A: Hairs on the sole of a gecko foot. These are broadened at the upper end.
B: Artificially produced gecko structure. The broad tops can also be seen here.
C: Image of the hierarchical structure in photoresist. This is the negative of the desired structure.
D: Image of the hierarchical structure in silicone. This was formed by replication using the structure shown in figure 1C.

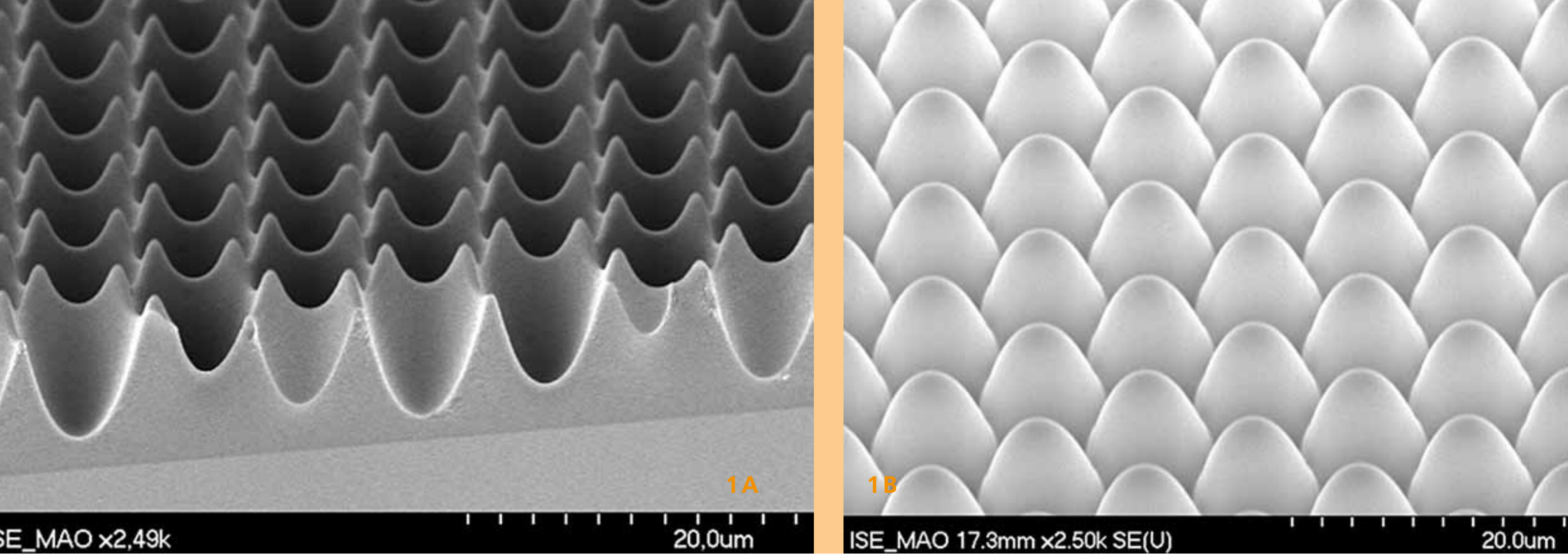


2 *Schematic processing sequence to produce hierarchical gecko structures. Silicone is shown in orange, exposed photoresist in yellow and unexposed photoresist is grey.*

With the new processes and materials, we have extended our repertoire of structures in the direction of combined structures with vertical side walls. Combined structures offer the advantage that several functions can be united in a single layer. This is of great interest especially for surfaces for optical applications.

The extension to large aspect ratios and the possibility even to replicate undercuts broaden the spectrum of applications for our technology enormously. It allows microstructured surfaces to be produced over large areas without seams.

The project on "Bioinspired Reversible Adhesives by Micro- and Nanopatterning Techniques", a joint project with the Leibniz Institute for New Materials (INM) and BASF, is funded by the Volkswagen Foundation.

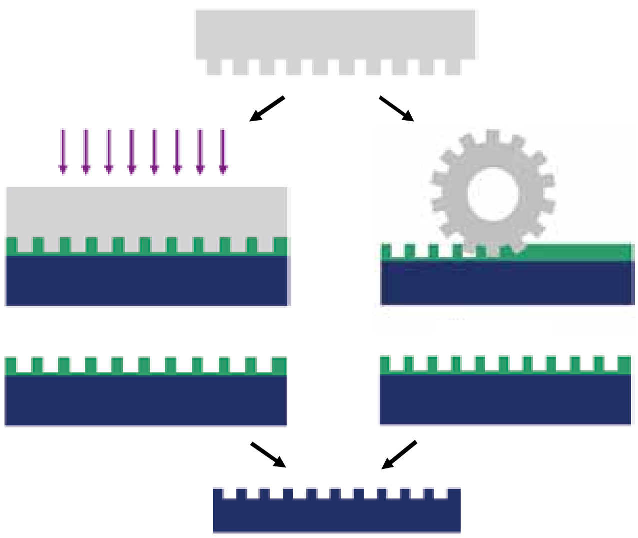


SILICON TEXTURING IN CONTINUOUS PRODUCTION

In the "Nanotex" project, we are developing processes to create defined textures for silicon solar cells which are suitable for mass production. The roller nano-imprint lithography which we apply is intended to allow honeycomb texturing of multicrystalline silicon in a continuous process. Another project objective is the production of diffraction gratings with sub-micrometre structures on the back surface of solar cells. These should raise the quantum efficiency specifically in the long-wavelength spectral region where silicon absorbs only weakly, and thus widen the technological window for the production process.

Benedikt Bläsi, Aron Guttowski, **Hubert Hauser**, Martin Hermle, Volker Kübler, Bernhard Michl, Claas Müller*, Marius Peters, Sebastian Schwarzkopf, Andreas J. Wolf, Werner Platzer

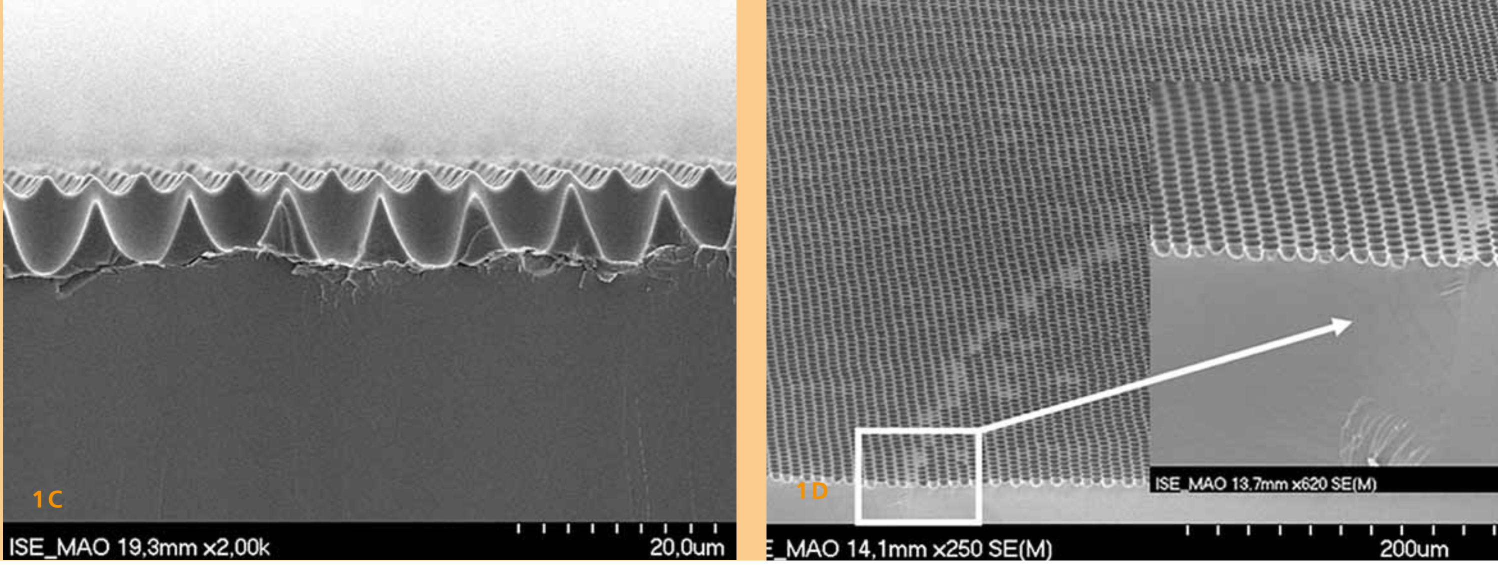
* IMTEK, University of Freiburg



The effect of texturing the front surface of Si solar cells to increase their efficiency has been known since the 1960's. On the one hand, the texturing reduces reflection losses due to multiple reflections. On the other hand it lengthens the pathway of light within the cell due to refraction effects. To date, only stochastic and usually wet-chemical etching processes without masks are used on an industrial scale to texture the Si surface. Due to the non-uniform crystal orientation in multicrystalline silicon (mc-Si), isotropic etching procedures are predominantly used. These indeed result in a homogeneous texture and thus in a homogeneous appearance but their anti-reflective effect is very much inferior to that of random pyramids on monocrystalline silicon (c-Si).

When the world record efficiency for mc-Si solar cells of 20.4 % was reached in 2004 at Fraunhofer ISE, not only had highest-efficiency processes been adapted for this substrate material but also so-called honeycomb texturing was applied to the front surface. As the photolithographic processes that were used on a laboratory scale to generate such hexagonal patterns are too expensive to be transferred to industrial production, we conceived an alternative processing sequence to implement defined textures. This alternative processing sequence is based on structuring an etching mask in an embossing process, so-called nano-imprint lithography (NIL).

2 *Schematic illustration of the processing sequence for texturing with nano-imprint lithography (NIL). NIL variants using a flat embossing die and a continuous roller-embossing process are shown.*



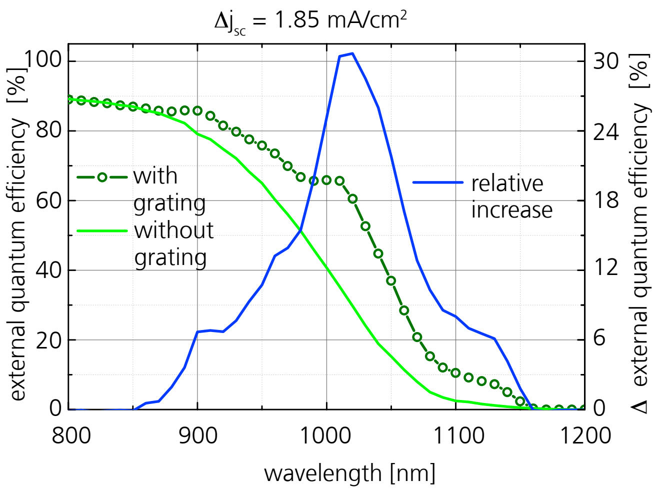
1 *Scanning electron micrographs of the structured surfaces after different processing steps. A: Hexagonal pattern with a period of 8 µm in a positive photoresist after interference lithography. This structure is used as a master. B: Silicone image of this master (inverse structure), which serves as the embossing die for the NIL. C: Photoresist structured by roller NIL on a rough multicrystalline Si wafer. D: Honeycomb-textured surface of a mc-Si wafer after plasma-etching processes to transfer the structure. A grain boundary is shown in the enlarged detail.*

As NIL is a replication procedure, initially so-called master structures must be created. We generate these with interference lithography, a process which allows a multitude of different structure types to be created with structure dimensions from 100 nm to 100 µm on substrate areas of up to 1 m². These master structures can be galvanically replicated many times, such that metal moulds for preparing the embossing dies become available. The embossing dies are made by casting from the moulds. The subsequent embossing of the etching mask is the process which is suitable for mass production. We use transparent and flexible embossing materials to structure UV-curable photoresists on rough mc-Si substrates.

In the "Microstructured Surfaces" group, we have now developed and constructed two facilities for NIL. In the laboratory version, a plane-parallel embossing die is used. In the second, extended version, the embossing die is already mounted on a roller, so that a continuous process and thus the integration into production lines become feasible. Roller embossing or imprinting processes represent well-established technology to structure flexible films. The special feature of the roller NIL facility which we have developed is that it can structure photoresist layers on stiff, non-transparent, rough and fragile substrates. After the etching mask has been structured with NIL on the Si substrate to be textured, the structure defined by the mask is transferred to the substrate by etching. Finally, the remaining photoresist must be removed and the substrates can be sent along the rest of the production line to make the final solar cells. The processing sequence for texturing is illustrated in figure 2.

Within the "Nanotex" project, this processing sequence based on NIL is being investigated for two model applications of texturing wafer-based crystalline Si solar cells. One application is the previously mentioned honeycomb texturing of mc-Si (or c-Si which does not have the standard <100> orientation) with structure dimensions in the micrometre range. The other application is the formation of sub-micrometre diffraction gratings on the back of the substrate, which is technologically more demanding. Both applications contribute to light management and are intended to increase the absorptance and thus the current generated by the cells. Figure 2 shows a simulation of the quantum efficiency as increased by a diffraction grating.

The modelling part of the presented work is carried out within the "Photonic Si" project. The "Nanotex" project is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).



3 *Results of electro-optically coupled simulations of a Si solar cell with and without a diffractive back-surface grating.*

HEATING, COOLING AND ELECTRIC POWER 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 fields. 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 with 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, which is incident on the earth as electromagnetic radiation, 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 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, depends not only on its surface properties, 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.

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 the base load. 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. Heat which is not generated from solar energy can still be provided renewably from biomass. By applying hybrid approaches or storing the thermal energy, the power stations can also supply electricity at night. In general, the concept of solar power plants is associated with large projects in the 20–400 MW_{el} range. However, we are also investigating the opportunities for medium-sized solar-thermal

© Andasol 1 - Paul Langrock/Zenit/laif

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

The Andasol 1 parabolic trough power station serves as a forerunner to the DESERTEC project. It is the first European solar-thermal power station with parabolic trough technology, in which the sunlight is focussed by reflectors onto a receiver pipe. Synthetic heat-transfer oil is heated by the concentrated solar energy. The resulting steam drives a power station turbine. Andasol 1 generates 50 MW electric power with 3800 full load hours per year. Fraunhofer ISE supports the development of solar-thermal components such as receivers and concentrator mirrors, and investigates questions concerning systems technology, such as optimal integration into the steam cycle.

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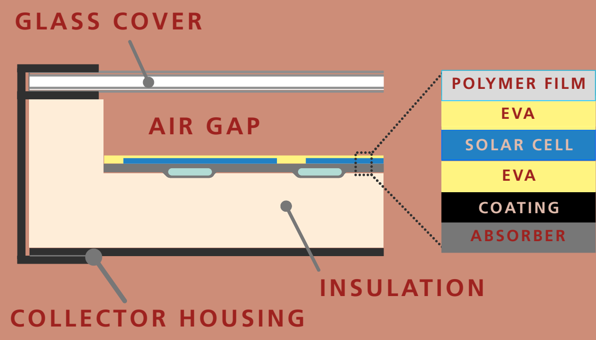


OPTIMISED PHOTOVOLTAIC-THERMAL HYBRID COLLECTOR

In principle, photovoltaic-thermal (PVT) hybrid collectors represent the most efficient way to use solar energy. In practice, however, they have not yet become established due to unconvincing electrical and thermal efficiency values. Clear improvements in the efficiency have now been achieved with a newly constructed PVT collector. This demonstrated that PVT collectors with appropriate configurations have advantages compared to classic thermal collectors and PV modules.

1 A / B *Prototype (A) and cross-section (B) of the optimised PVT collector.*

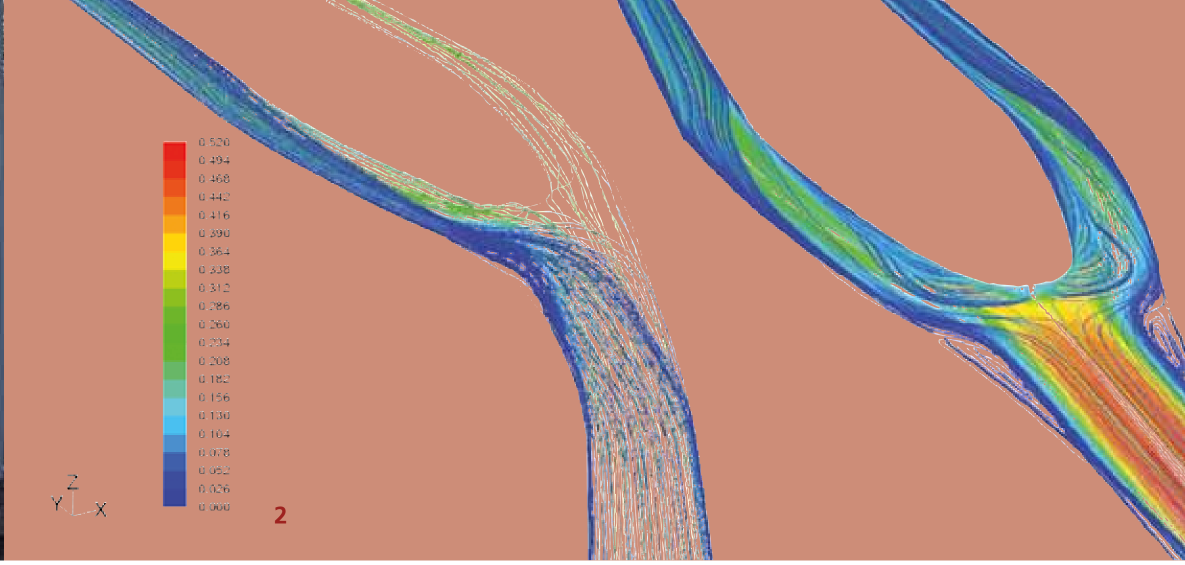
Patrick Dupeyrat, Michael Hermann, **Gerhard Stryi-Hipp**, Harry Wirth, Werner Platzer

A PVT flat-plate collector typically consists of a PV module which is attached by adhesive to an absorber plate with its piping for the heat-transfer medium and mounted in a collector housing. As a result, the electricity yield is reduced by the additional glass pane and the higher cell temperatures, and the solar thermal yield is also lower due to the poor heat transfer from the cell to the heat-transfer fluid and the higher thermal losses due to lack of a selective coating. There is a conflict regarding the optimisation goal, as the solar cell with its negative temperature coefficient should preferably be operated at lower temperatures whereas a satisfying solar-thermal yield demands higher working temperatures.

On commission to Électricité de France (EDF), a clearly optimised PVT collector was developed within the "PVTcol" project. Due to its modified construction and new production process, it features significantly higher efficiency than standard PVT collectors. In this optimised PVT collector, an aluminium roll-bond absorber was used, which has the FracTherm® channel structure for homogeneous flow distribution on one side and is flat on the other side. The crystalline solar cells were laminated onto the flat surface of the roll-bond absorber. The solar cells are attached to the absorber sheet by an EVA film which also serves as electrical insulation. Due to the direct lamination, the thermal conduction from the solar cell to the heat-transfer medium was significantly improved. The application of a thin polymer film with a low refractive index as the cover for the solar cells led to a clear increase in the transmittance compared to glass and an EVA film. As the module-absorber unit is located within the collector housing, the polymer film provides sufficient protection for the solar cells. A glass pane with anti-reflective coatings on both surfaces was used as the transparent cover for the collector.

This specific configuration eliminates two critical disadvantages of previous PVT constructions: the reduced optical efficiency and the lower thermal conductivity. Accordingly, both the electrical and the thermal efficiency values for the optimised PVT collector are significantly higher than for a standard PVT collector.

In a follow-up project, the objective is to improve the thermal yield also at higher operating temperatures and thus to further increase the thermal efficiency value. New concepts are also planned to prevent destruction of the photovoltaic laminate due to higher stagnation temperatures. If this succeeds at acceptable costs, the PVT collector will become a very attractive alternative to separate photovoltaic modules and solar-thermal collectors.



SOLAR COLLECTORS WITH BIONIC FRACTHERM® ABSORBERS

For several years, we have been developing solar absorbers which have multiply branching fluid channels similar to the veins of a leaf or blood vessels, and thus achieve low pressure losses and a homogeneous flow distribution. Within the EU-funded "BIONICOL" research project, we have successfully designed and measured the first prototypes with dimensions typical of commercial collectors.

1 Prototype of a solar collector with commercially typical dimensions (aperture area: 1.9 m²) with a bionic FracTherm® solar absorber.

2 Streamlines as a result of CFD simulations (Computational Fluid Dynamics) to investigate flow phenomena in FracTherm® bifurcations. Complex, three-dimensional effects such as secondary flows (Dean vortices) occur.

Maximilian Bauch, Wolfgang Graf, **Michael Hermann**, Philipp Hofmann, Hans-Martin Keyl, Lotta Koch, Karin Lunz, Christoph Thoma, Werner Platzer

The energy efficiency of solar absorbers depends on both the heat transfer from the absorber surface to the heat-transfer medium and the pressure drop which must be overcome by the pump. In earlier small-scale investigations, we were already able to demonstrate that the bionic FracTherm® absorber structure which we had developed results in a lower pressure drop and a more homogeneous flow distribution than conventional meander or harp channel designs, while retaining high thermal efficiency. This technology is now being applied for the first time to collectors with typical commercial dimensions within the EU-funded "BIONICOL" project. Roll-bonding is the production process applied and the material used is aluminium.

After production of the solar absorber and suitable treatment of the surface, a spectrally selective coating based on a CrO_x cermet was deposited in our sputter coater. The coated solar absorber was mounted in a collector housing with a construction corresponding to that of a production series. We measured a collector that was produced in this way (fig. 1) in our solar simulator under standard conditions. The collector efficiency factor F' was determined to be 0.96. This is a very good value, considering that the flow through the absorber is almost entirely laminar. Roll-bond technology generally makes very high thermal efficiency values feasible. However, an important feature distinguishing the FracTherm® absorber is that a much lower pressure drop was measured in it than in roll-bond absorbers with other channel structures.

Within the "BIONICOL" project, we also carried out simulations and experiments to better understand the flow behaviour in FracTherm® bifurcations and allow future optimisation (fig. 2). To this purpose, we applied Computational Fluid Dynamics (CFD) for three-dimensional simulations, one-dimensional flow calculations and measurements and visualisations with a newly developed fluid dynamic test rig. In contrast to conventional T or Y bifurcations, the region near the fractal bifurcations did not show any sudden pressure drops in the simulations. This theoretical result thus confirmed the pressure drop measurements on FracTherm® absorbers very well.

The industrial partners in the "BIONICOL" project are TiSUN GmbH, CGA Technologies SpA , INTERPANE Entwicklungs- und Beratungsgesellschaft mbH and TYFOROP Chemie GmbH. The project is supported by the European Commission.

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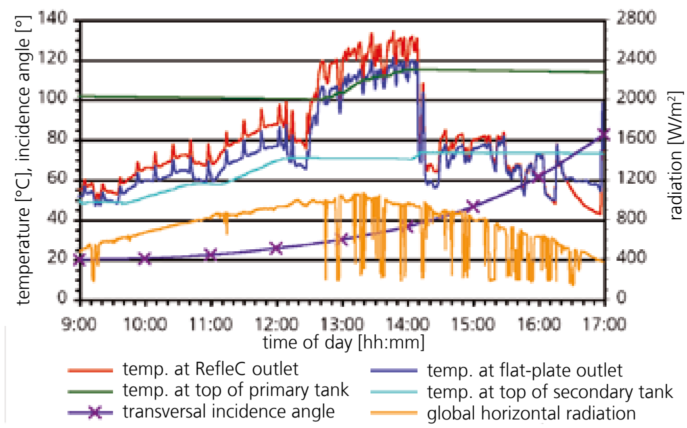

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SOLAR PROCESS HEAT – COLLECTOR DEVELOPMENT AND SYSTEM MONITORING

Solar generation of industrial process heat is becoming increasingly important. 23 % of the industrial heat demand in Germany is for temperatures of less than 100 °C and a further 10 % for temperatures below 150 °C. During the past three years, we have supported the Wagner & Co. Solartechnik company in developing the RefleC collector, which was optimised for operating temperatures between 80 °C and 150 °C. A pilot system was installed in June 2010.

Stefan Heß, Michael Klemke, Paolo Di Lauro, Axel Oliva, Werner Platzer

The RefleC collector is a flat-plate collector with a double-layer cover (anti-reflective solar glass and a polymer film). A segmented stationary reflector is attached to its lower edge and reflects additional solar radiation onto the collector. We optimised the reflector geometry and the basic collector with the help of ray-tracing and yield simulations. Particular attention was paid to use of diffuse radiation, which is significant at our latitudes, and its influence on the annual energy yield of the collector. For validation, we carried out extensive measurements on four test samples in our TestLab Solar Thermal Systems. In addition to determining the incident angle modifier (IAM), the efficiency characteristic and the acceptance of diffuse radiation, the collector functionality was also tested.

The pilot plant of the Laguna laundry in Marburg (Lahn) has an aperture area of 57 m². The primary storage tank and the two parallel secondary tanks each have a volume of 1 m³. The solar loop is operated with a pressure of 6 bar because of the high operating temperatures of up to 130 °C. The storage tanks are pressurised and filled with water at temperatures up to 120 °C (primary) and 110 °C (secondary). The system provides heated water to two low-temperature processes and

1 *RefleC collector trough (pilot system): The sub-structure for the reflectors supports the row of collectors in front of it, which are not equipped with reflectors and act as a reference.*

2 *Analysis of the tank loading from the RefleC collector compared to the flat-plate collector (Wednesday, 14.7.2010). The reflectors are most effective for an incidence angle of 25 °; they are no longer active above 45 °.*

one high-temperature process in the laundry. At the process level, a separate storage unit with hot water for the washing machines is heated from 20 °C to 80 °C. The laundry draws steam from a steam network which is supported by solar thermal energy at two integration points. Only about 50 % of the condensate is recovered, because a considerable share of the steam is used directly. For this reason, the additional water required for the boiler can be pre-heated from 20 °C to up to 90 °C by solar energy. In order to demonstrate the performance of the collectors and the system at high temperatures, the boiler feedwater is additionally pre-heated in summer from 90 °C to a maximum of 120 °C.

With our monitoring, we compare the operating performance of the RefleC collector with that of the basic collector (double glazed flat-plate collector without reflectors). We analysed the strong dependence of the collector output on the incidence angle of the radiation in more detail and made recommendations to avoid stagnation and to optimise control of the collector and the charging loops. In addition, we are investigating the integration of solar heat into the three processes it supports. On the basis of our measured data, we adapted the flow rates for the collector field sub-sections and the control parameters to the behaviour of the new collector.

The work was supported within the "Solarthermie2000plus" Programme by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).

SOLAR-THERMAL DESALINATION OF SEAWATER

Drinking water that is provided by desalination of seawater has become a fully accepted part of life in some parts of the world. Solar energy is often an excellent source of energy for this application due to the prevailing geographical conditions. At Fraunhofer ISE, thermally driven membrane distillation systems have been developed which serve to prepare drinking water from seawater, but can also be used in industrial separation processes. Operation is driven by thermal solar energy or by waste heat.

Florian Groß, Mario Hillebrand, **Joachim Koschikowski**, Martin Rolletschek, Daniel Pfeiffle, Rebecca Schwantes, Marcel Wieghaus*, Daniel Winter, Hans-Martin Henning

* PSE AG

1 *Solar-driven membrane distillation system for desalination of salty brackish water in the north of Namibia. The system is completely integrated inside a 20-foot freight container. In the foreground are the membrane expansion vessel, the cooling tower and the inlet water tank. The extreme ambient temperatures of less than 0 °C in winter and more than 50 °C in summer present a major challenge to the technology.*

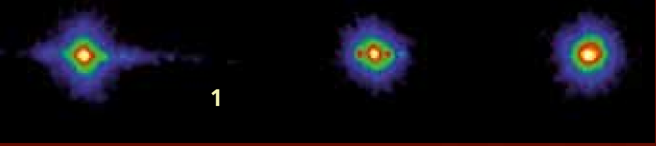
2 *Membrane distillation system driven by waste heat to desalinate seawater on the Italian island of Pantelleria in the Mediterranean Sea. The system produces extremely pure water with an electrical conductivity of less than 5 µS.*

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 MD modules which include integrated heat recovery and thus use the energy very efficiently. We integrate these modules e.g. into solar-driven desalination plants.

In July 2010, we installed a solar-thermally driven desalination unit for brackish water in a village in the north of Namibia. The installation was part of the "CuveWaters" joint research project, which is supported by the German Federal Ministry of Education and Research (BMBF). The system is supplied with heat from a collector field with an area of 225 m^2 and is dimensioned for a maximum daily capacity of 5 m^3. The desalination system, including the 12 m^3 hot water tank is housed in a 20-foot container. The electric system components are supplied with photovoltaic power, so fully autonomous operation is possible.

We have developed a further membrane distillation system together with an international consortium within an EU-funded project. This system also has a daily capacity of 5 m^3, but is driven by the waste heat from a diesel engine in a power station on a small island south of Sicily. By using the waste heat, the system can be operated for 24 h a day at its optimum operating point and is not subject to daily and seasonal fluctuations.

We have equipped both systems with extensive measurement instrumentation so that the operation data can be analysed intensively. In addition, we installed two smaller, solar-driven membrane distillation systems with a maximum daily capacity of 150 l in Tunisia as part of the EU-funded project.



CHARACTERISATION OF NEW MATERIALS FOR PARABOLIC-TROUGH REFLECTORS

The optical properties of reflector materials decisively influence the efficiency of concentrating collectors for solar-thermal power stations and process heat. Thus, we have developed a series of processes and models for detailed optical characterisation of new reflector materials. We investigate e.g. the reflection behaviour of aluminium or polymer-film reflector systems and determine the effect of beam expansion on the energy yield of a collector by optical simulation (ray-tracing).

Anna Heimsath, Gregor Kutscheidt, Peter Nitz, Werner Platzer

In concentrating solar collectors, as much of the direct solar radiation as possible should be reflected via the reflectors onto the absorber pipe. Both for the selection of the key component, the reflector, and for simulating the energy yield of the collector, knowledge of the optical reflectance for all relevant incidence angles is essential. This applies particularly for reflectors based on aluminium or polymer films. They feature a particularly anisotropic scattering characteristic (fig. 1) and are often inadequately characterised by standard methods and models.

In our laboratory, we measure relevant optical properties such as the angle-dependent, direct-direct reflectance, the beam expansion by the reflector surface and the form stability of reflectors which are mounted e.g. in parabolic troughs. In particular for new reflector materials of multi-layer stacks, we determine the angle-dependent, direct-direct solar reflectance for incidence angles up to 60 °, as interference effects can have a strong effect here. The resulting function can then be transferred directly for use in the yield analysis of a collector system.

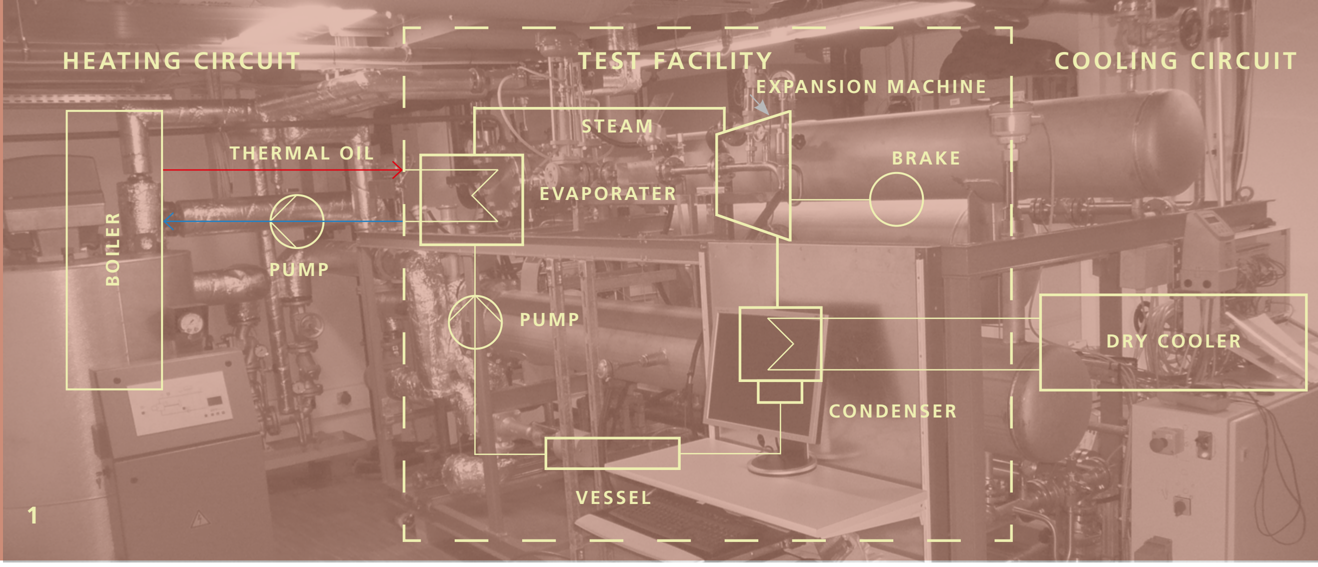
1 *Reflectance profile of an aluminium-based reflector (left), a back-surface glass mirror (centre) and a reflector based on multi-layer polymer films (right).*

2 *Lasergoniometer for detailed characterisation of the angle-resolved reflectance profile of reflector materials (laser beam included by photomontage).*

To obtain information on the characteristic scattering profile of a reflector, we use our laser and white-light goniophotometers (fig. 2). With them, we measure the angle-resolved profile of a reflected light beam typically at intervals of 0.1 ° and extract from it the parameters for a modelling function to describe the scattering behaviour of the surface. For example, we model aluminium-based reflectors with two Gauss distributions and an exponential function. Rolling traces on the reflector sheet cause an anisotropic scattering distribution which we must include in our optical simulations to obtain realistic results.

We determine the three-dimensional curvature and form stability of a reflector by fringe reflectometry (deflectometry). In this technique, a camera records the distortion of a dynamic sinusoidal pattern as reflected by the mirror. The distortion is analysed and from this, the local surface angle of the reflector is determined over the entire reflector area or the section recorded by the camera. The extremely high sensitivity of the method makes it feasible to identify smallest deviations in the surface angle of less than 1 mrad and thus to detect manufacturing faults and defects.

The methodological results of our work contribute to the standardisation activities of IEA Solarpaces Task 3. The project is supported by industrial partners.



LABORATORY FOR SOLAR-THERMAL POLYGENERATION IN OPERATION

In future, the generation of electricity, heat and/or cooling power by concentrating solar collectors could replace fossil fuels in industrial plants in sunny regions. After a study (MEDIFRES) had demonstrated the economic viability of such systems, a laboratory was established at Fraunhofer ISE to develop them further. The new "Polygeneration Laboratory" enables us to test components for solar-thermal applications and to develop controllers for the entire system.

1 *Schematic diagram of the heating, steam and cooling circuits in the test facility. The background photo shows the laboratory for solar-thermal polygeneration at Fraunhofer ISE, which was completed in 2010.*

Max Klein, **Anton Neuhäuser,** Peter Nitz, Daniel Willert, Werner Platzer

The solar-thermal power stations which have been built up to now are in the power range above 10 MW_{el}. Systems in a lower power range have higher specific costs but offer advantages concerning the financing and more rapid technological development resulting from a large number of systems. Higher specific costs can be compensated by combined usage of the collectors for electricity generation, provision of process heat and/or cooling power, desalination of seawater and the resulting increase in efficiency. In this way, small and medium-sized systems in the power range between 50 kW_{el} and 10 MW_{el} can present an economic option to reduce CO_2 emissions and gain independence from rising fuel prices. Such systems become particularly interesting if they replace electricity from diesel generators. These are used where there is no public electricity grid or it is unreliable. For example, 30 % of the industrial electricity consumption in India is supplied by generators belonging to the manufacturing companies.

In order to test and further develop the key components (storage tank, expansion machine, chiller) of a polygeneration system, we have established a new laboratory. The main purpose of the laboratory is the characterisation and further development of system components for use with the fluctuating heat yield of a concentrating collector. Specifically the partial load performance and the transient behaviour of component are often inadequately known. Furthermore, control strategies for individual components and the entire system can be tested and optimised to ensure a reliable and optimally efficient supply to the consumer. A gas boiler, which can imitate the performance of any arbitrary collector array at different locations, enables the laboratory to be operated independently of the prevailing solar irradiation in Freiburg.

The test facility at Fraunhofer ISE is designed such that both water and organic working fluids can be used. This means that both classic steam-based processes and Organic Rankine Cycles (ORC) can be investigated for the electricity generation. With a thermal power of up to 250 kW, the gas boiler can heat a thermal oil circuit up to 300 °C. The hot thermal oil can then be fed either into a thermal storage tank or to the evaporator. Evaporation pressures of up to 30 bar can be reached thereby. With the help of a brake, expansion machines with power of up to 40 kW_{el} can be investigated flexibly at different rotational speeds under full and partial load conditions. Our palette of services is rounded out by computer simulations and studies which visualise how an experimentally determined start-up or partial-load characteristic affects a complete system for solar-thermal polygeneration.

ELECTRICITY FROM SUNLIGHT

SILICON PHOTOVOLTAICS

Photovoltaics has experienced a boom for several years, which was stimulated particularly by the targeted market introduction programmes in Germany, Italy and other European countries: The globally installed power capacity has already increased to more than 25 GW.

More than 80 % of the rated power is generated by 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 the epitaxial production of silicon films, the analysis of diverse silicon feedstock materials including novel substances, and materials and processing issues concerning the relevant types of technology. Our centre includes a crystallisation facility, with which 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 adapting the crystallisation processes to each particular type of solar silicon. Among other aspects, we are conducting intensive research on upgraded metallurgical grade (UMG) silicon.

A central activity of our ETAlab is the development and analysis of high-efficiency solar cell concepts and processes. ETA stands for Efficiency, Technology and Analysis. The goal is to achieve higher efficiency values with thinner wafers and thus provide the pre-requisite for substantial cost reduction in silicon photovoltaics. 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 m^2, which has allowed us to set several international records for efficiency. In addition, further laboratory area of 900 m^2 is available for us to develop effective surface passivation methods, novel metallisation and doping procedures, innovative nano-structuring technology and new characterisation methods.

Concerning the crystalline thin-film solar cell, we are conducting research on the concept of a wafer equivalent. A high-quality thin film is deposited from gas containing silicon onto inexpensive substrates. The result looks like a wafer and can be processed into a solar cell in a very similar way to conventional wafers for solar cells. As very small amounts of high-purity silicon are needed, the wafer equivalent concept is largely independent of the supply situation for solar silicon, allowing very dynamic market growth.

After extending our Photovoltaic Technology Evaluation Centre PV-TEC to an area of more than 1200 m^2, 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. 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.

Solar cells must be durably encapsulated to protect them against weathering. There is still considerable potential for increasing quality and reducing costs in this field. We are working on new module concepts and materials combinations, also for thinner, large-area solar cells and those with contacts only on the back surface. Deeper understanding of aging mechanisms and procedures to characterise them play a key role in our contribution toward increasing the long-term quality of photovoltaic modules.

Our activities on silicon solar cells in Freiburg are complemented by the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen (see article on p. 74), the Technology Centre for Semiconductor Materials THM in Freiberg, Sachsen, which is operated jointly with Fraunhofer IISB, and the Centre for Silicon Photovoltaics CSP in Halle, which is operated jointly with Fraunhofer IWM (see article on p. 58).

Solar cells with back-surface contacts represent an interesting variant among novel solar cell concepts. The complete metallisation of these cells is on the back surface, so that the surface facing the light is free of shading and is fully available for converting the incident solar radiation into electricity. With the highly efficient laser-drilling process illustrated in the photo, we produce several thousand so-called vias per second. These vias conduct the current which has been collected on the front surface through highly doped silicon regions to the back surface. We achieved an efficiency value of 18.8 percent for such emitter wrap-through (EWT) solar cells with an industrially relevant process at Fraunhofer ISE.

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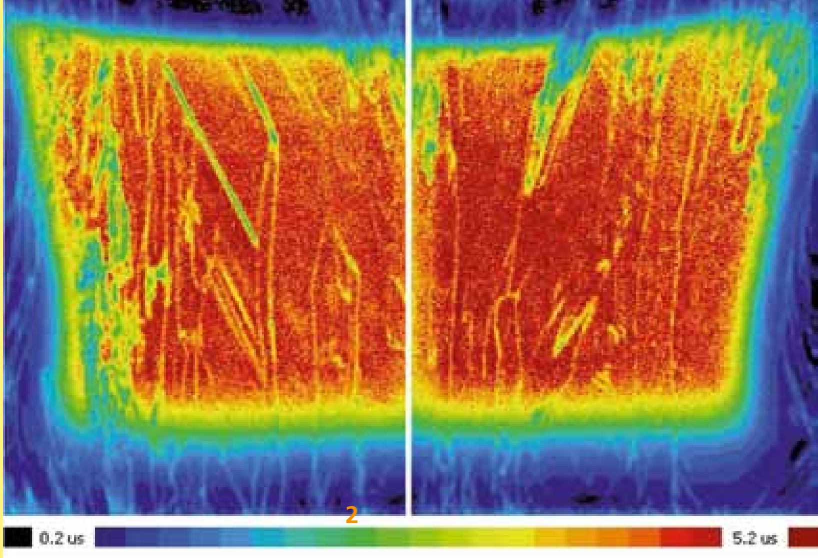

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CRYSTALLISATION DEVELOPMENT FOR MULTICRYSTALLINE SILICON

The crystallisation development for multicrystalline silicon blocks at the Silicon Material Technology and Evaluation Centre SIMTEC is aiming for higher material quality and yield. For directional solidification, we are investigating new crucible systems with extremely pure coatings and adapted gas flushing. Block processing and wafering facilities as well as measurement systems to analyse blocks and wafers allow comprehensive production and characterisation of samples at SIMTEC.

1 *Quartz crucible with feedstock before crystallisation (left) and a multicrystalline block (right) in the G1 research format, corresponding to 15 kg of silicon.*

2 *Spatial distribution of lifetimes (MW-PCD) over a cross-section through a G2 block. The reduced lifetime at the edges due to impurities from the crucible is clearly visible.*

Fridolin Haas, Philipp Häuber, Teresa Orellana, **Stephan Riepe**, Claudia Schmid, Mark Schumann, Matthias Singh, Bernd Weber, Yaniss Wencel, Andreas Bett

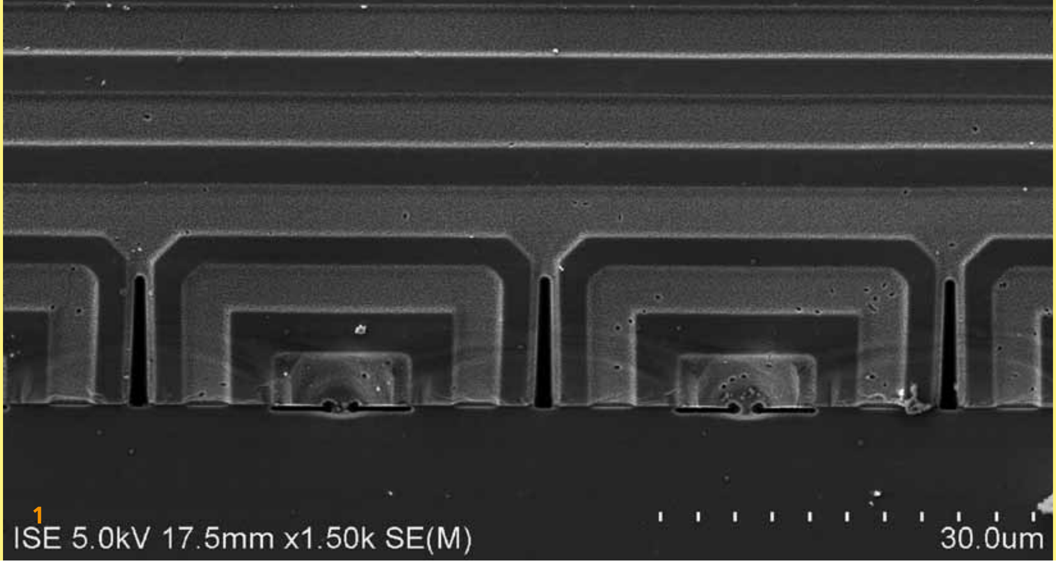
One focus of the crystallisation work in the SIMTEC laboratory is further development of multicrystalline silicon for highly efficient solar cells. We use an industrially relevant Vertical Gradient Freeze (VGF) system to produce multicrystalline test blocks in the research dimensions G1, corresponding to 12–15 kg, and G2, corresponding to 75–80 kg of silicon material. We study aspects of material quality such as the formation of the crystalline structure or the introduction of impurities with the small G1 blocks. From one block, we can obtain up to 300 wafers in standard dimensions to produce solar cells and experimental structures, as well as samples for the analysis of impurity elements. These are currently being used to analyse various Si materials (e.g. UMG silicon) and to evaluate new crucible coatings.

Aspects of processing technology are primarily investigated with the larger G2 blocks. These include analysing the temperature fields in different processing steps and optimising the gas atmosphere. We support the experimental work by simulation of the temperature distributions and gas flows with the help of a commercial computational fluid dynamics (CFD) program. With up to 2200 wafers per G2 block, there is scope for diverse analyses and developments in the solar cell process accompanied by statistical analysis.

For both block dimensions, we have established standards with a crystallisation quality which is comparable to current industrial material. By optimising the furnace construction and gas flushing, we were able to achieve a substantial improvement concerning the introduction of carbon and reduction of the number of silicon carbide inclusions. The behaviour of coatings during the melting and solidification phases is investigated both in the VGF system and also in an experimental reflector furnace. The aim of the coating development is to prevent adhesion of the silicon to the crucible and reduce the introduction of impurities into the molten silicon.

For further processing of the blocks on site, a complete sawing line including cleaning is in operation. We use it for flexible preparation of bricks, wafers and specially dimensioned samples for our research projects and external clients. An industrial process is applied to clean the wafers, which ensures a high throughput and good surface purity.

The work is supported by the Fraunhofer-Gesellschaft within the "Silicon Beacon" project.



TOWARD EPITAXIAL HIGH-EFFICIENCY WAFER EQUIVALENTS

Epitaxial wafer equivalents present the simplest concept to combine the advantages of Si wafer solar cells with those of thin-film solar cells: low production costs and high efficiency. In working toward this goal, we are presently concentrating on light management in the cell so that more electricity can be generated with a thinner layer thickness.

Marion Drießen, Elke Gust, Mira Kwiatkowska, Harald Lautenschlager, **Stefan Reber**, Philipp Rosenits, Andreas Bett

In so-called epitaxial wafer equivalents, where the photovoltaically active layer of crystalline silicon is only about 20 µm thin, up to 20 % of the incident energy is lost (in addition to other unavoidable losses) if "light management" is not applied. We aim to exploit this untapped potential for increasing the efficiency by a simple approach: The light is coupled obliquely into the layer and encounters an efficient mirror with a reflectance exceeding 90 % at the back of the layer. Whereas the first effect can be implemented relatively simply by roughening the front surface with suitable etching methods, the second condition is much more difficult to achieve. The reflective layer must not only reflect light but also reproduce the crystalline structure of the substrate, as the required electronic quality of the Si layer cannot be obtained otherwise.

The technique which we are applying is so-called "Epitaxial Lateral Overgrowth" (ELO), which is known from microelectronics. In the dielectric reflective layers, small openings through to the Si substrate are made, in which the deposited Si layer nucleates and then grows together with few defects over the reflective layer. Our main task is to implement this process, which has been too expensive for solar cell production up to now, with inexpensive equipment and technology.

1 *ELO layer on a monocrystalline substrate with a SiO_2 reflector. The different stages of growth have been made visible by deliberately varied doping.*

Our investigations up to now have produced promising results. We were able to prove that high-quality Si layers on single-layer SiO_2 reflectors could be produced in cost-effective deposition reactors constructed specially for photovoltaics, even at very high deposition rates. The monocrystalline substrate which was used for this purpose is transferred very well crystallographically for optimally oriented openings. Other crystal orientations, e.g. for multicrystalline substrates, can be overgrown equally reliably. Here, we are currently working to reduce the higher defect densities we have observed to acceptably lower values. Our measurements on reflection in the corresponding samples are very pleasing: as predicted by the simulation of a completely continuous SiO_2 reflector, the ELO layers feature strongly increased reflectance in the interesting long-wavelength range. Even for the relatively low surface coverage of the SiO_2 reflector of 90 %, the measured value still follows the theoretical curve very closely, opening possibilities to simplify the process. The ELO process can be made cost-effective by allowing the required openings to form randomly by deliberate manipulation of the chemical composition of the reflector layer and suitable temperature steps. The first ELO experiments with these reflectors have demonstrated the fundamental feasibility of overgrowth. Almost perfect optical properties are obtained with multi-layer reflectors. The first examples based on silicon carbide, silicon nitride and aluminium oxide have already been produced and tested for ELO.

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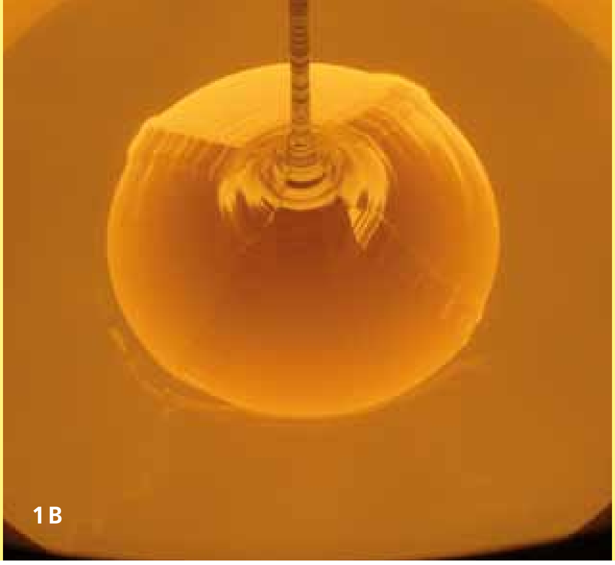

1 B


1 C

LABORATORY FOR CRYSTALLISATION TECHNOLOGY AT FRAUNHOFER CSP IN HALLE

The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle was established jointly by Fraunhofer ISE and Fraunhofer IWM and is managed by both institutes together. The most modern equipment for crystallisation of silicon for photovoltaics is installed in the laboratory for crystallisation technology LKT at Fraunhofer CSP. In industrial facilities, we produce monocrystalline ingots by the Czochralski process and multicrystalline blocks by the Vertical Gradient Freeze method. Beyond this, we are working to establish float-zone technology to produce solar cell wafers. The systems were successfully taken into operation for research work.

Rainer Barth, Stefan Köstner, Joachim Prause, Stephan Riepe, Heiko Wust, **Andreas Bett**

Work at the Fraunhofer Centre for Silicon Photovoltaics CSP is divided into the two departments, "Reliability and Technology for Grid Parity" (CSP-ZTN) and "Laboratory for Crystallisation Technology" (CSP-LKT), which interact closely with each other. CSP-LKT conducts research, currently under the interim leadership of Dr Andreas Bett, 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 PVA Tepla company is available to us for further development of the Cz process. After taking it into operation in 2010, in cooperation with PVA we were able to establish a standard process, with which we can produce Cz ingots with a mass of app. 60 kg, a diameter of app. 205 mm and a length of app. 60 cm. Initial analyses of the material have demonstrated very good material quality for a doping range which is close to the industrial standard. After a standard process, the estimated lifetime in the bulk crystal is longer than 300 µs, with good homogeneity over the length of the ingot (fig. 2). The research work on Cz crystallisation focussed on investigating the crucible and its effect for longer processing times, and optimising the process management, particularly concerning the cooling profile.

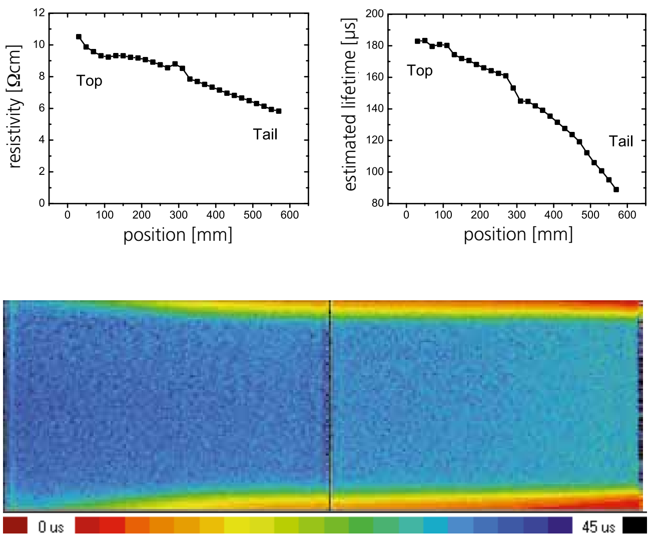
Growing crystals according to the float-zone procedure results in single crystals with the best material quality, from which solar cells with the highest efficiency can be produced. However, the material is not significantly represented on the PV market due to the high production costs at present. The 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 3" diameter and variable length in a laboratory facility (Model Fz14). Initial analyses have demonstrated good material quality with charge carrier lifetimes of up to 8 ms.

The third technology which we are developing further is the crystallisation process according to the Vertical Gradient Freeze (VGF) principle. We use industrial equipment from the PVA Tepla company (Multicrystallizer), with which multicrystalline blocks weighing up to 450 kg can be produced. Our work is concentrating on questions concerning process optimisation and reduction of carbon impurities introduced into the crystal. The work is carried out in close consultation with research on the VGF process at Fraunhofer ISE. Further processing and analysis of all the produced crystals is carried out in cooperation with CSP-ZTN and Fraunhofer ISE.

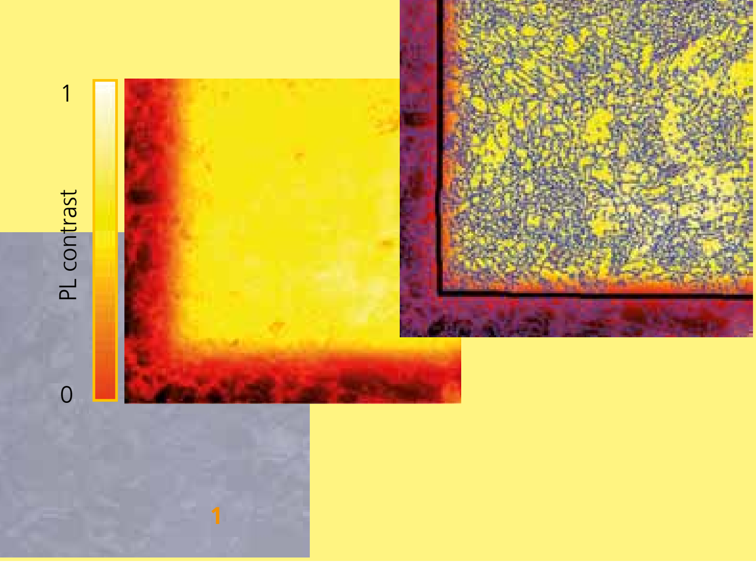
The work is supported by the German Federal Ministry of Education and Research (BMBF) within the "Cz-Sil" and "Fz-Sil" projects in the "Solarvalley Mitteldeutschland" Cluster of Excellence.

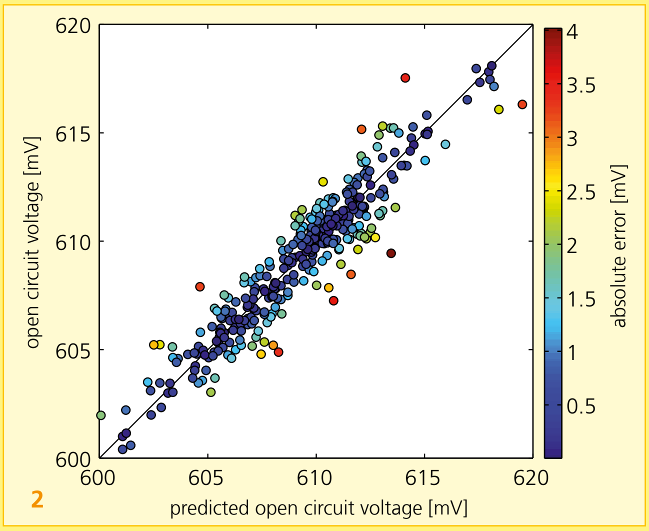
1 *Production of monocrystalline silicon according to the Czochralski process (Cz), with illustrations on page 58 of the crucible filled with feedstock (A), the nucleation phase (B) and the final crystal (C).*

2 *Production of monocrystalline silicon by the float-zone process (FZ): Melting zone (A) and final 3" crystal (B).*



3 *Electrical analysis of a Cz ingot of 600 mm length and 205 mm diameter, with measurements of the resistance (upper left), the lifetime (upper right) and the local distribution of the effective lifetimes (below).*





QUALITY EVALUATION OF MULTICRYSTALLINE SILICON WAFERS

Photoluminescence imaging (PLI) is a promising method for early evaluation of the material quality of mc-Si wafers, as various crystal defects can be made visible with high spatial resolution. In order to adapt the method to in-line application, robust algorithms for automatic detection and quantification of superimposed defect structures in the PL images were developed at Fraunhofer ISE. By applying pattern recognition techniques, we were able to determine the material quality quantitatively and predict the solar cell quality on the basis of PLI measurements from the as-cut phase.

Matthias Demant*, Markus Glatthaar, Jonas Haunschild*, **Stefan Rein**, Ralf Zeidler, Ralf Preu

* Freiburg Materials Research Centre FMF, University of Freiburg

1 Digital photo (left) and PL image (centre) of an untreated mc-Si wafer. The PL image shows typical crystallisation defects, which are visualised more clearly in the processed result (right). The dark regions along the edge of the PL image indicate impurities arising from the crystallisation crucible, which are identified by an adaptive threshold procedure (black line). Defects in the crystal structure appear as linear structures. These can be reliably detected within the PL image despite strong contrast fluctuations, as is visible from the blue lines in the processed result.

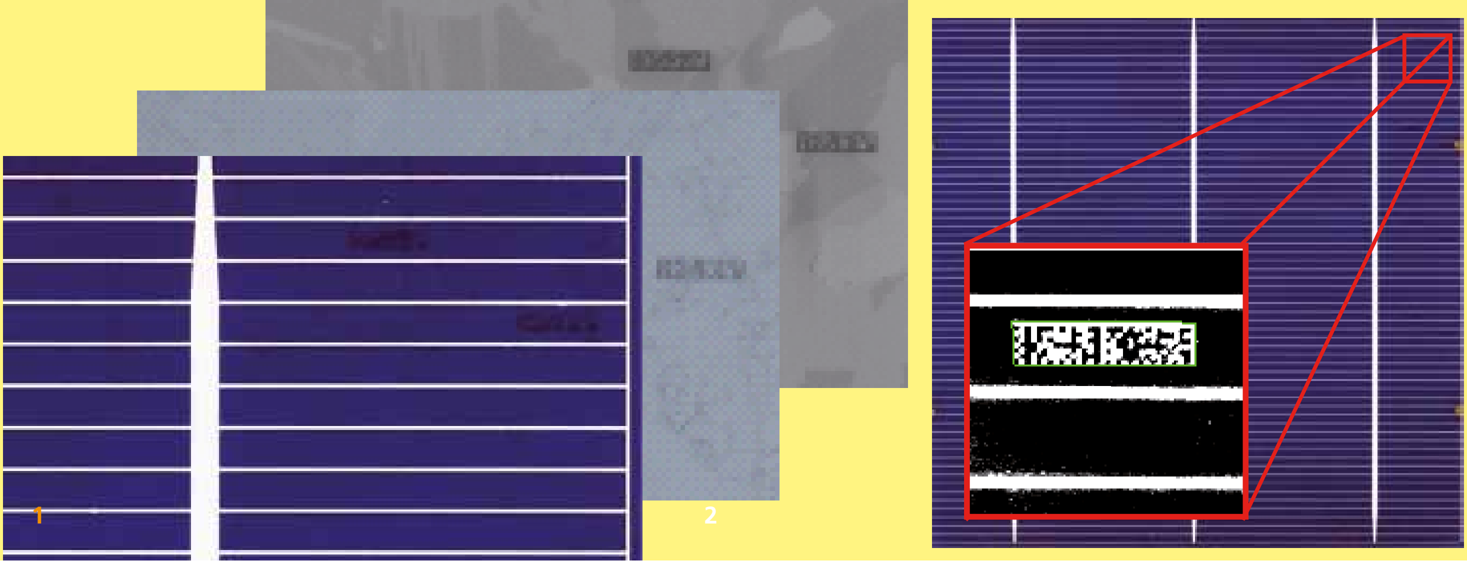
2 Physically relevant characteristics were extracted from the PL images and a model was established to predict the open circuit voltage. The graph shows the strong correlation between the predicted and the measured open circuit voltage for a sample of 365 industrially prepared solar cells with strongly varying material properties.

The efficiency value of mc-Si solar cells depends strongly on the electrical material quality of the wafers used. This is determined by crystal defects and impurities which are incorporated during crystallisation. Many of these defect structures are already visible in PL images of the as-cut wafers, so that this information is already available in principle for quality rating (fig. 1). To make it feasible to use this information for in-line material control, we have developed procedures to automatically detect and evaluate the quality-related characteristics.

A particular challenge to automated analysis of PL images is presented by the superposition of different types of defect structures. In addition, when widely varying material is analysed, strong fluctuations in the image intensity and contrast occur. The developed algorithms feature robust and exact detection of the defect structures and guarantee fine discrimination between different quality levels. In addition to determining the area ratio of crystal defects, defect-rich and contaminated regions are reliably quantified, as are inhomogeneities in the PL signal.

The significance of this physically relevant description of the material properties was verified by pattern recognition methods. Based on a neural network, a prediction model could be trained to determine the open-circuit voltage of the final solar cell on the basis of the material description. The strong correlation between the measured open circuit voltage and the value predicted from the unprocessed wafer in fig. 2 shows that the wafer description developed here from the extracted characteristics is a suitable measure for evaluating the electrical material quality of the wafer.

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



WAFER IDENTIFICATION WITH DATA MATRIX CODES

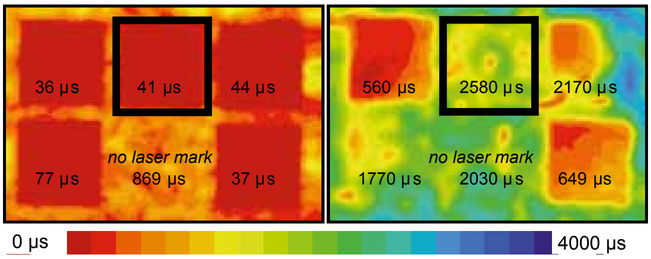
Precise process and quality control, which allows measurement data to be correlated over many different processing steps, demands that wafers be identified by applying and reading a scannable code on the wafers themselves. Laser marking is a suitable method to produce such robust structures inexpensively. However, as this can significantly damage the Si crystal, the development of a suitable marking process and scanning system presents challenges concerning both the technology and measurement.

Christian Harmel, **Alexander Krieg, Stefan Rein**, Christian Schmitt, Albrecht Weil, Ralf Preu

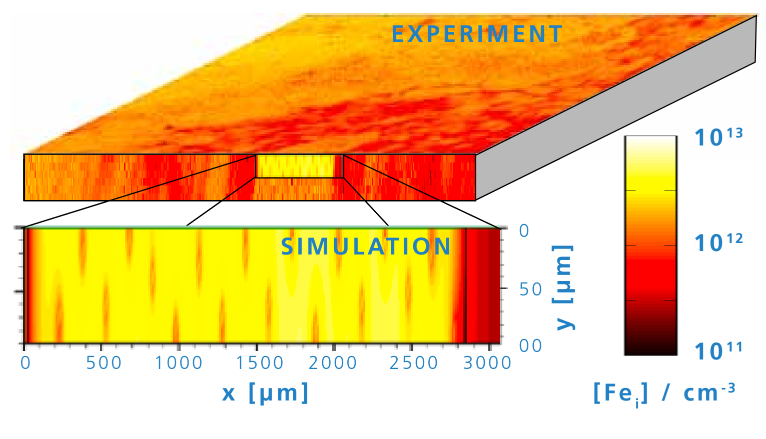
Robust tracing of individual wafers in industrial production lines with a high throughput demands unambiguous wafer marking which allows the wafer to be actively identified by a detection system at every processing step. At Fraunhofer ISE, a system for wafer identification has been developed which is based on a data matrix code (fig. 1), which is engraved with a laser onto the wafer at the beginning of the solar cell production process and can be read with a special reading system. As the code is located on the front of the wafer, the solar cells can even be identified in the module, which allows them to be traced back through the entire value-added chain. Because the code is thus within the active cell area, it must not affect the performance data of the solar cell adversely. The spatial distribution of lifetimes shown in figure 2 demonstrates that the damage to the crystal induced by our optimised laser process is so slight that it is completely eliminated by the usual removal of material in the wet-chemical texturing step. Nevertheless, the code structure is retained throughout the etching process, which is the pre-condition for robust scanning along the entire processing chain. As the reflectance of the wafer surface is systematically reduced by several etching and coating steps during the production process, the major challenge is to detect codes with very weak and inhomogeneous contrast. Our scanning tests with a specially adapted scanner from the SICK company have shown that data matrix codes with an area of 1.2 x 4.8 mm² and a code element width of down to 150 µm can be reliably engraved and read out again with a recognition rate of 98 % along the complete solar cell manufacturing process. In some individual steps, recognition rates of 100 % have already been achieved. As there is still potential for improvement, it appears feasible to develop the procedure into a robust tracking system.

The work is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) within the "QUASSIM" project and by the SICK AG company.

1 *Data matrix codes marked on wafers in the as-cut state and after texturisation, and on the final solar cell (left). Enlarged image of a data matrix code (code area: 5.8 mm²) between the contact fingers of a solar cell (right).*



2 *Lifetime topographies of the laser-marked structures after laser marking (left) and after etching (right). After the laser-marking process, the lifetime and thus the material quality is reduced compared to the reference surface without laser marking. For an optimised laser process (squares), this lateral damage can no longer be detected after one standard etch removal step.*



SIMULATION OF THE IRON CONCENTRATION IN SILICON SOLAR CELLS

Iron, the most important impurity in multicrystalline silicon solar cells, limits their potential efficiency. The iron concentration and its incorporation in the silicon depend essentially on the cell process. Depending on the feedstock impurity, the crystal quality and the exact temperature profile, it is now possible to calculate and optimise the precipitate dimensions as well as the total and interstitial concentration of iron.

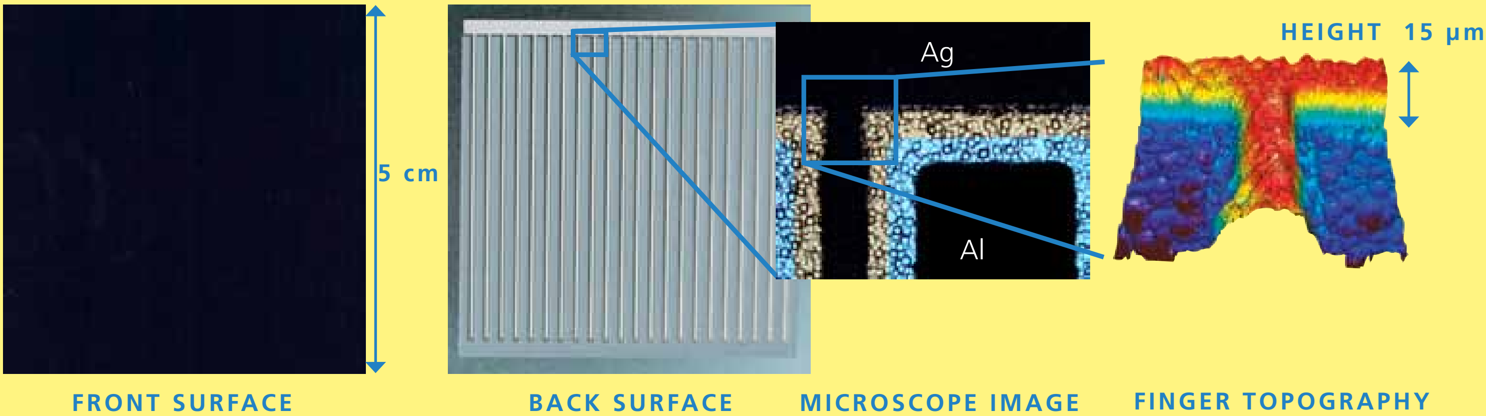
Holger Habenicht, Jonas Schön, **Martin Schubert**, Wilhelm Warta, Stefan Glunz

Iron impurities cannot be avoided cost-effectively at present, because they occur both in the feedstock and particularly in the crucible walls of the crystallisation furnaces. However, the silicon can be improved considerably during the solar cell manufacturing process: The material is purified by segregation of iron atoms in the phosphorus-doped emitter or in the back-surface aluminium layer, and finely distributed atomic iron can be concentrated at a few positions by precipitation in silicon. These effects are very sensitive to the temperature profile of the solar cell processes. In order to optimise these, simulation of the process-dependent iron distribution is very valuable. We have therefore developed a simulation based on the Sentaurus Process™ software platform, which can predict the iron concentration, distribution and configuration as a function of the processing parameters. The iron distribution is determined on the basis of the iron content of the feedstock material, taking diffusion processes out of the crystallisation crucible walls into account. A simulated section, which corresponds to the typical values for the multicrystalline sample analysed experimentally, is shown in figure 1. The typical heterogeneous distribution of nucleation sites is taken into account. The simulation results are checked by comparing the simulated values for the interstitial iron concentration with those determined from PLI measurements. An example of a high total iron concentration of 10^{16} cm^{-3} in figure 1 demonstrates the agreement between experiment and simulation.

1 Comparison of the interstitial iron density after crystallisation as determined experimentally (sample surface shown in perspective) and calculated by simulation.

In the same way, the next step in the solar cell process can be simulated, namely the phosphorus diffusion, which strongly reduces the interstitial iron concentration. Only the phosphorus concentration of the doping gas ($POCl_3$) and the exact temperature conditions are needed for the simulation. The growth of phosphoric glass and the formation of the emitter are emulated by the simulation. Thus, the effect of controlled temperature gradients on the iron precipitation and the preceding temperature steps to dissolve precipitates before the phosphorus diffusion can be evaluated to determine optimal conditions for internal and external gettering. Finally, the last high-temperature step in the solar cell process was investigated: firing the electrical contacts. During this step, decomposition of iron precipitates competes with gettering effects due to segregation in the phosphorus-doped emitter and the aluminium back surface. For Si wafers with a given dislocation density and known impurity of the feedstock materials, it is now possible to estimate an important factor limiting the cell efficiency, namely the iron distribution in the solar cell, and to reduce its effect by process optimisation.

The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and by the Fraunhofer-Gesellschaft within the internal "Silicon Beacon" project.



1

HIGHLY EFFICIENT, SCREEN-PRINTED N-TYPE BACK-CONTACT SOLAR CELLS

One of the least expensive and most widely used structuring processes in the PV industry is screen-printing. The use of n-doped Si material is very promising, as this is very well suited to the production of solar cells with back-surface contacts and junctions, which have a high potential efficiency. Interestingly, the required p-doped emitter for n-type solar cells can be obtained by alloying aluminium, so that the emitter and the metallisation can be produced at the same time. This approach is pursued in the work presented here. To this purpose, aluminium pastes are applied locally onto the wafer by screen-printing. In this way, highly efficient, back-contact solar cells can be produced with robust, industrial screen-printing processes. Efficiency values of up to 20.0 % have been achieved.

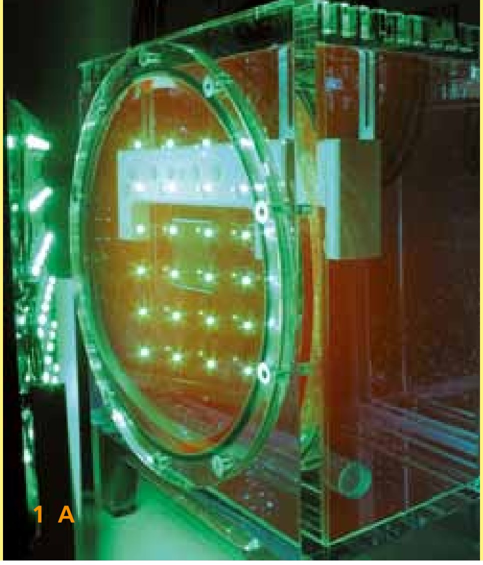
Daniel Biro, Roman Keding, Jonas Krause, Karola Rühle, Robert Woehl, Ralf Preu

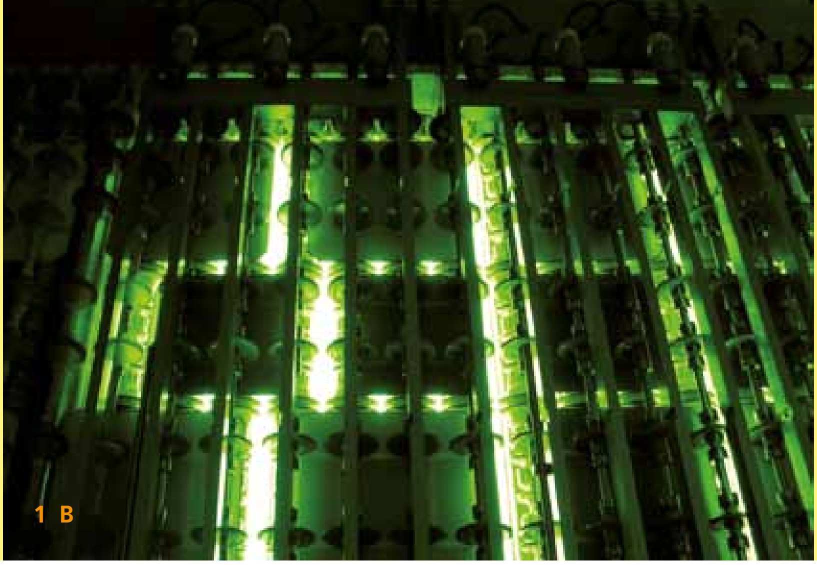
1 *The front surface of the produced solar cell (left) is optimised for maximal light absorption and is passivated over the entire area. The back surface of a highly efficient BC-BJ solar cell with screen-printed contacts (edge length 5 cm) features an interdigitated grid structure. The light areas mark the silver contacts and the darker areas correspond to aluminium, which functions simultaneously as the emitter doping, metal-to-semiconductor contact and electricity conductor. The intermediate zone is passivated. On the right is the image from a topographic measurement by confocal microscopy, with which the height of the metal fingers can be measured.*

In back-contact, back-junction (BC-BJ) solar cells, both polarities of the solar cell are located on the back surface of the Si wafer (fig. 1). This avoids the shading by the metal contact grid which is usual in standard solar cells. However, this raises a challenge to the structuring of the back surface, as the electrical structures must be interdigitated without causing short circuits. Over the past few years, screen-printing technology and the associated materials have made enormous progress and have contributed to great increases in efficiency for the standard solar cell. In addition, the improved machine accuracy now allows complex structure to be printed very exactly.

For our purposes, we use commercially available pastes, facilitating the subsequent transfer to industrial production. These materials can be processed by screen-printing and thus used to create emitter structures on n-type wafers. n-type wafers are particularly advantageous for BC-BJ cells, as they feature the long charge-carrier lifetimes which are needed to achieve high efficiency values. In this work, we have investigated how we can form a precise structure with screen-printing processes, in order to then combine this with the metallisation, which is also screen-printed.

With the developed procedures, solar cells were produced for the first time which have an efficiency value of 20.0 % for an aperture area of 3.7 x 4.5 cm^2 (10 Ωcm, FZ Si). Encouragingly, we have already identified potential for further improving the efficiency value to above 21 %, which means that this comparatively simple structure is distinguished by excellent chances for industrial implementation.





COPPER-BASED CONTACTS FOR SILICON SOLAR CELLS

Continuous growth of PV is only to be achieved by constant cost reduction and finally by grid parity. To increase the efficiency of solar cells, multi-step processes for metallisation have been developed at Fraunhofer ISE for many years. In the work presented here, an additional approach is followed of replacing expensive silver by less expensive copper. By using a suitable barrier material, a slim, highly conductive, cost-effective and durable solar cell contact has resulted.

Jonas Bartsch, Katharina Bay, Sebastian Binder, Birte-Julia Godejohann, Matthias Hörteis, Mathias Kamp, Andrew Mondon, Stefan Glunz

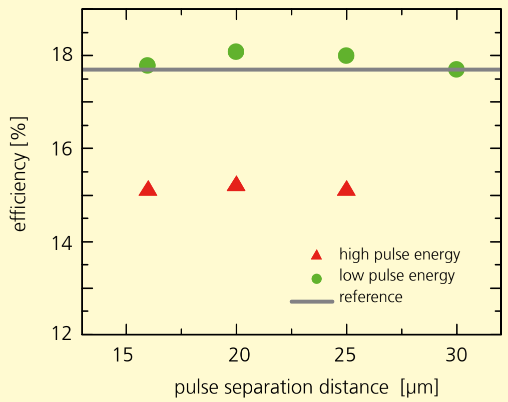
1 *Production equipment for light-induced electro-plating of metal at Fraunhofer ISE: flexible laboratory equipment (A) and an industrial in-line facility (B).*

The front contacts of Si solar cells are mostly produced today by screen-printing silver pastes. This usually results in shading of 7–10 % of the cell area. The paste materials also represent a considerable share of the production costs. The new approach pursued here extends the concept of two-step metallisation from a thin seeding layer and a highly conductive, electro-plated conducting layer (shading < 6 %). By adapting existing or developing new processes, alternative contact materials are introduced which act as a suitable diffusion barrier for copper. With almost the same conductivity, copper is less expensive than silver by a factor of almost 100. However, its unfavourable diffusion and defect properties in silicon pose a challenge for using it technologically to metallise solar cells, particularly concerning the long-term stability of solar modules, for which there is usually a performance guarantee for 25–30 years.

An essential pre-condition for the process development is evaluation of the long-term stability. To this purpose, a method was specifically developed to test the new contact systems quickly and elegantly.

To deposit seeding and barrier layers, sputtering processes and the favoured, cost-effective electrochemical processes are used. The costs thus remain low, despite additional processing steps. The use of nickel on printed seeding layers or for the electrochemically deposited seeding layer on silicon has shown very promising results. The limit to the module lifetime, which was determined to result from possible copper diffusion, was found to be several hundred years for optimised coating systems, which clearly exceeds requirements.

Fundamental understanding of the processes and the degradation behaviour were gained from laboratory experiments with industrial Cz solar cells of 50 x 50 mm^2 area. Efficiency values of up to 18 % have been achieved up to now, accompanied by excellent long-term stability. The next goal is to transfer the optimised processes initially to solar cells with industrial dimensions and then to industrial production machines. For these developments, a new technological hall with a floor area of 450 m^2 became available to us in 2010.



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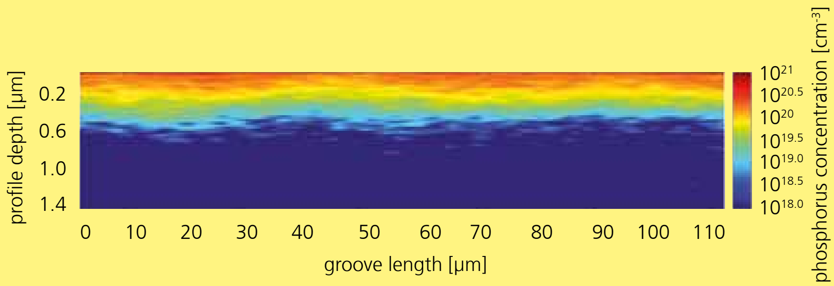

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LASER-CHEMICAL PROCESSING (LCP) FOR SELECTIVE-EMITTER SOLAR CELLS

A high-resistance emitter can increase the efficiency value of a solar cell. It allows better passivation, greater sensitivity to blue light and lower surface recombination rates. However, the contact resistance between a metal finger and the emitter must simultaneously be reduced by a selectively highly doped zone, as a high-resistance emitter is difficult to contact with industrial technology. Laser chemical processing (LCP) offers the opportunity to create locally highly doped regions and to simultaneously open existing passivation layers.

Walter Eipert, Andreas Fell, Christoph Fleischmann, **Filip Granek, Sybille Hopman**, Sven Kluska, Kuno Mayer, Matthias Mesec, Stefan Glunz

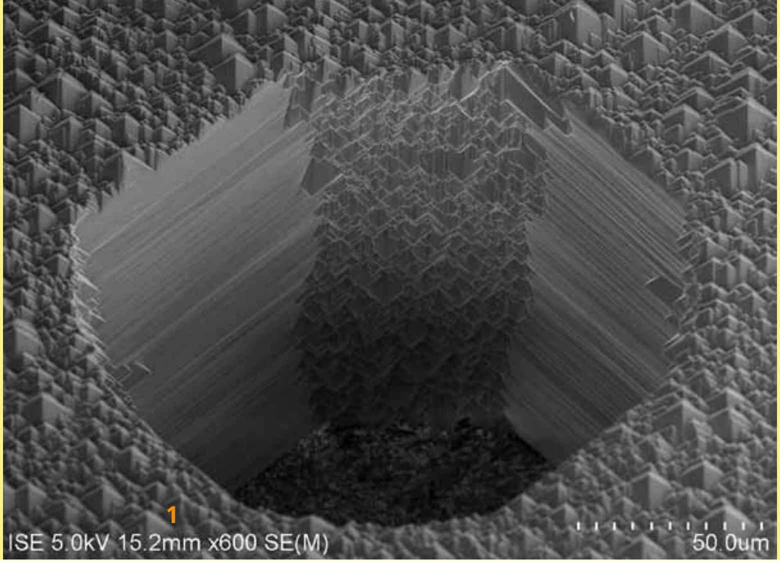
In order to demonstrate the increase in efficiency caused by use of a selective emitter, screen-printed solar cell structures were produced on a high-resistance (80 Ω/sq) emitter and a low-resistance (55 Ω/sq) emitter. Under the metal fingers, the selective emitter was created by LCP with low and high laser pulse energy. As expected, the references without LCP structures showed a higher fill factor (78.2 %) for the 55 Ω/sq emitter than for the higher-resistance emitter (77 %), which is attributed to the better contact resistance.

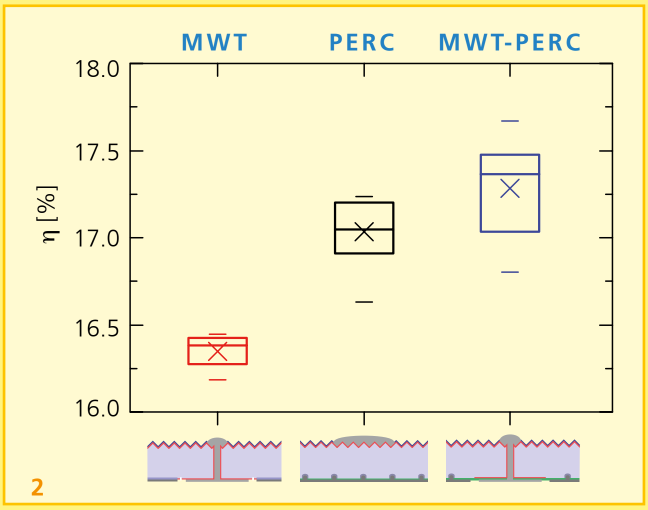
The results for the solar cell efficiency in figure 1 show that higher efficiency values can be obtained for low laser pulse energy values over a wide range of pulse separation distances. An efficiency value which is up to 0.4 % (absolute) higher than the reference value is achieved for an LCP solar cell with optimal laser parameters for a 20 µm pulse separation distance. Even higher increases can be achieved by using alternative metallisation approaches like Ni/Cu. In the case of the screen-print used here, the fill factor is increased to 78.5 %, which indicates the improvement in the contact resistance due to the selective emitter. With regard to an industrial application, this is an important result, as it demonstrates that a high processing speed of up to several metres per second is possible. Figure 1 also shows the efficiency values for solar cells produced with high laser pulse energy. The efficiency values all lie below the reference values, which is due to destruction of the space charge zone by laser-induced damage. The charge carrier recombination rate increases in the damaged area.

The two-dimensional linear profile in figure 2 is based on a three-dimensional secondary ion mass spectrometry (3-D SIMS) measurement. In comparison to the widely known SIMS, the detection limit for this 3-D SIMS is at higher phosphorus concentrations. Thus, phosphorus can be detected only down to 10^{18}–10^{19} cm^{-3}. The profile shows an uninterrupted, homogeneously doped selective emitter, for low pulse energy and a short pulse separation distance. A highly doped area with a concentration of more than 10^{20} cm^{-3} extends into the silicon to a depth of 300 nm. In this region, the phosphorus is homogeneously distributed over the entire length of the cross-section, which can be attributed to multiple melting and solidification processes due to the short pulse separation distance. The profiled line with a length of app. 120 µm was melted 80 times in total. This additionally meant that many phosphorus atoms were able to diffuse into the silicon, making the doping profile more homogeneous.

1 LCP solar cell efficiency values versus pulse separation distance for high and low pulse energy, compared to reference cells without selective emitters under the metal fingers.

2 Linear profile from a 3-dimensional SIMS measurement for a laser groove prepared with a low pulse energy and short pulse separation distance.





MWT-PERC: OUR NEW CONCEPT FOR INDUSTRIALLY RELEVANT BACK-CONTACT CELLS

The MWT-PERC concept combines the advantages of back-surface contacting with passivation of the surface. This allows novel module concepts to be applied and significantly increases the efficiency compared to conventional solar cells. Efficiency values of up to 18.8 % (monocrystalline) and 17.7 % (multicrystalline) for large-area MWT-PERC solar cells were achieved at Fraunhofer ISE with industrial production processes.

1 Laser-drilled opening for wrap-through contacting in a monocrystalline Si wafer after wet-chemical processing.

2 Efficiency values achieved for different cell concepts with multicrystalline silicon. The solar cell area is 156 x 156 mm². The graph shows the median (horizontal bar), average (x), quartile (box) and extreme values (-). The results were achieved in cooperation with an industrial partner.

Daniel Biro, **Florian Clement**, Tobias Fellmeth, Elmar Lohmüller, Alma Spribille, Benjamin Thaidigsmann, Andreas Wolf, Ralf Preu

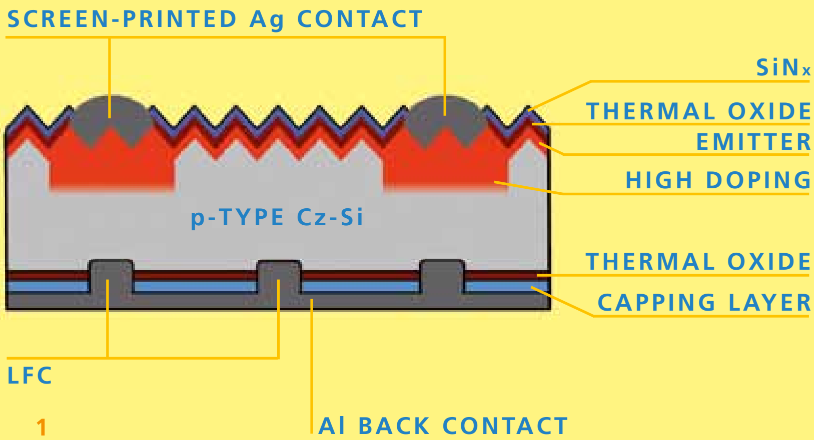
The avoidance of external contacts on the front of the solar cell (MWT concept: metal wrap through), optimised back-surface reflection, surface passivation and the introduction of local back contacts (PERC concept: passivated emitter and rear cell) are the main advantages of the MWT-PERC concept. On the one hand, they increase light absorption considerably and significantly reduce recombination losses on the other. Thus, a clear increase in efficiency can be achieved in comparison to the conventional Si solar cell. In addition, surface-passivated back surfaces allow the use of very thin Si wafers as the starting point. In contrast to back-junction solar cells, the charge carriers are separated at the front of the solar cell. This lowers the demands on the material quality.

The aim of our research is to develop industrially applicable and economically viable production processes for MWT-PERC solar cells. Core steps of conventional solar cell processes are further developed using the demonstration platform of our Photovoltaic Technology Evaluation Centre (PV-TEC), thus enabling rapid transfer to industrial production. The manufacturing process which we have developed uses exclusively screen-printing technology to produce the metal contacts on the front and back of the solar cell. Thermally grown silicon oxide or dynamically deposited aluminium oxide is used for passivation.

Efficiency values up to 17.7 % have been achieved on multicrystalline Si wafers with an edge length of 156 mm. The efficiency value increases to 18.8 % if large-area monocrystalline Si material (Cz-Si) is used. The high efficiency level was also confirmed for very thin Si material (initial thickness of app. 120 µm).

Furthermore, a simplified production sequence for MWT-PERC solar cells was developed, which requires only one additional processing step compared to the reference process for preparing passivated solar cells. The additional effort to integrate external back contacts of both polarities is thus restricted to making the holes for the wrap-through contacting. The efficiency values that were achieved with the simplified production sequence are comparable to those for previously produced MWT-PERC solar cells.

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



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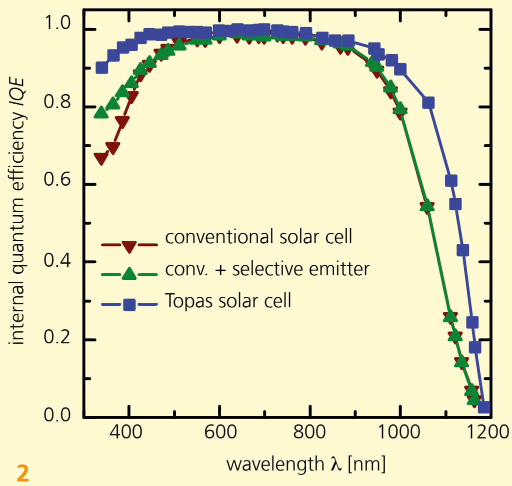


2

TOPAS: DOUBLE-SIDED OXIDE-PASSIVATED AND LOCALLY LASER-DIFFUSED SOLAR CELLS

Passivated surfaces allow the solar cell efficiency to be increased, as they reduce recombination losses. A further approach to increase efficiency consists of introducing selective emitter structures. At Fraunhofer ISE, a solar cell process was developed which combines the advantages of both approaches and makes efficiency values of around 19 % feasible.

Udo Belledin, Daniel Biro, Ulrich Jäger, Gero Kästner, Sebastian Mack, Edgar Allan Wotke, **Andreas Wolf**, Ralf Preu

Processes to fabricate crystalline Si solar cells with dielectrically passivated back surfaces are currently being transferred to industrial production. In comparison to conventional solar cells, which are completely metallised over the back surface, the dielectric passivation layer causes a reduction in surface recombination and improved light trapping, leading to a clear increase in efficiency. A further approach to increase the efficiency, which is being pursued intensively, is to implement selective emitters. Instead of the entire front surface being homogeneously doped, a heavily doped zone is created under the front contact grid and a moderately doped zone is formed between the contact fingers. This structure reduces recombination in the emitter and simultaneously ensures a low contact resistance between the emitter and the contact finger.

Both approaches are combined in the TOPAS solar cell structure (Thermal Oxide Passivated All Sides) which was developed at Fraunhofer ISE (fig. 1). Both the front emitter and the back surface are passivated by a thin, thermally grown silicon oxide layer, which is formed simultaneously on the front and back surfaces of the solar cell by a short oxidation process. Single-sided, wet-chemical etching processes are used to condition the back surface, so there is no need for masking steps. The LFC technology (laser fired contacts), which was also developed at Fraunhofer ISE, is applied for local contacting of the back surface. The heavy local doping under the front contacts is implemented by laser diffusion. The phosphorus silicate glass, which is present after the diffusion process, serves as the dopant source.

1 Schematic diagram of the TOPAS solar cell structure.

2 Comparison of internal quantum efficiency of different solar cell types.

Figure 2 shows the internal quantum efficiency of three different solar cell types: While the conventional, completely metallised back surface is retained, the introduction of a laser-diffused selective emitter already raises the yield in the short-wavelength spectral range. Additional passivation of the emitter by a thin, thermally grown oxide layer for the TOPAS solar cell further increases the cell sensitivity for blue light. The superiority of the passivated back surface, by contrast, is evident particularly in the higher quantum efficiency for the long-wavelength spectral range.

In our PV-TEC pilot production line, TOPAS solar cells were fabricated from large-area, Czochralski (Cz) silicon wafers with efficiency values of up to 18.9 %* and open circuit voltages of up to 645 mV*. This corresponds to an increase in efficiency of about 1 % (absolute) compared to conventional monocrystalline solar cells.

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

* Measurement with the PV-TEC cell tester after the fabrication process.

SUB-µm RESOLUTION TO DETERMINE RECOMBINATION AND DOPING

Many high-efficiency solar cell concepts feature small-scale structures such as local back contacts or selective doping on the front or the back of the cell. Established measurement methods have not previously been able to determine the recombination properties and analyse selectively doped structures with adequate lateral resolution. By application of microscopically resolved photoluminescence spectroscopy and microscopically resolved Raman spectroscopy, it is now possible to determine the Shockley-Read-Hall lifetime and the doping concentration with high spatial resolution.

Paul Gundel, Friedemann Heinz, **Martin Schubert**, Wilhelm Warta, Stefan Glunz

The detection of band-to-band luminescence of optically excited charge carriers has proved to be a very successful approach to detect the excess charge carrier density and thus the charge carrier lifetime. Nowadays, whole wafers can be analysed in seconds by photoluminescence imaging with a spatial resolution of about 100 µm. In addition to the restrictions imposed by the CCD camera used, in particular the lateral diffusion of charge carriers acts against still finer resolution.

Although the accuracy which can be achieved is adequate for many analytical purposes, particularly high-efficiency solar cells often contain structures which are of smaller scale than this resolution. Thus, the recombination properties of a laser-fired back contact can be detected only by their large-area effect on the charge carrier density.

1 *Measurement of a silicon sample with microscopically resolved photoluminescence spectroscopy.*

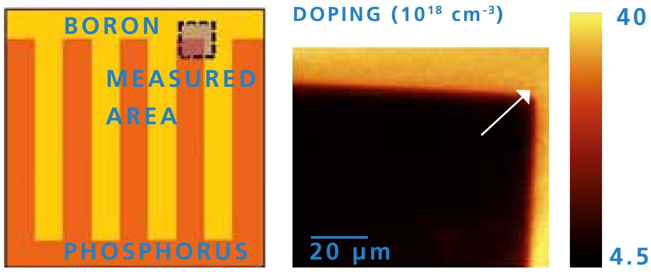
We have now succeeded in achieving significantly finer resolution by applying a trick: Instead of illuminating the sample homogeneously by a laser with a relatively low photon flux density, in the new procedure luminescence is excited by a focussed laser with a wavelength of 532 nm and is measured spectrally. A confocal microscope with a connected spectrometer and a linear-array camera replaces the CCD camera.

By concentrating the light spot to have a diameter of 0.5 µm, very high injection densities can be achieved. Thus, Auger recombination restricts the diffusion length of the dependence of the photoluminescence signal in this injection range on the excess charge carrier density, and the confocal detection, allow the effective measurement spot to be limited to < 1 µm. Although the advantages in resolution are obtained at the cost of significantly longer measurement times to scan a sample area and higher demands on the surface preparation, the decisive point is that it is now possible for the first time to obtain quantitative measurement values of the Shockley-Read-Hall lifetime with such fine spatial resolution. To achieve this, effects from the sample surface, the optics and the spectral detection unit must be eliminated. This can be done by evaluating the quotient of two measurements with different depths of field instead of a single absolute signal. The quotient is independent of all linear effects on the measurement signal. The quotient can be interpreted with the aid of a two-dimensional numerical simulation of the charge carrier density in the sample, which takes account of both the Auger and the Shockley-Read-Hall recombination. By comparing the simulated values with the measured ones, both the Shockley-Read-Hall lifetime and the doping concentration can be determined. The achieved spatial resolution of 0.8 µm is a major improvement on the previously applied measurement methods to determine the charge carrier lifetime. With this microscopic resolution and its strong sensitivity for short charge carrier lifetimes and high doping concentrations, the developed method is particularly well suited to detailed characterisation of microscopic doping structures. In addition to the spatially resolved doping concentration, possible damage due to the doping process can be measured directly and the solar cell process can be optimised efficiently.

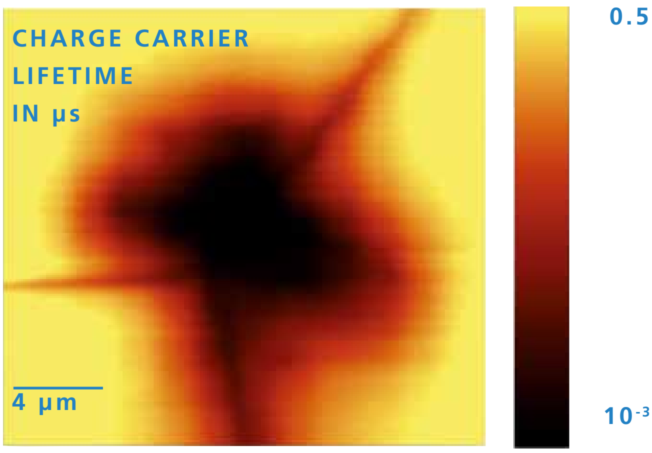
The potential of the measurement method is illustrated by the back surface structure of a solar cell shown in figure 2, where both contacts are integrated onto this single surface. The two different doping zones can be clearly recognised. The measurement also reveals a microscopic fault in the doping process (arrow), which can be avoided on the basis of this measurement. The measured doping densities were confirmed by electrocapacity-voltage measurements.

Just as promising as the application of microscopically resolved photoluminescence to technological microstructures is its use to investigate microscopic defects such as precipitates, dislocations and grain boundaries. The quantitative lifetime measurement of a nickel precipitate is shown with sub-micrometre resolution in figure 3. The fine spatial resolution means that the influence of individual defects on the charge carrier lifetime and changes during the solar cell process can be analysed separately.

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



2 *Doping structure on the cell back surface (left) and the doping density resulting from the photoluminescence measurement (right).*



3 *Lifetime measurements around a nickel precipitate at a three-way grain boundary with microscopically resolved photoluminescence.*

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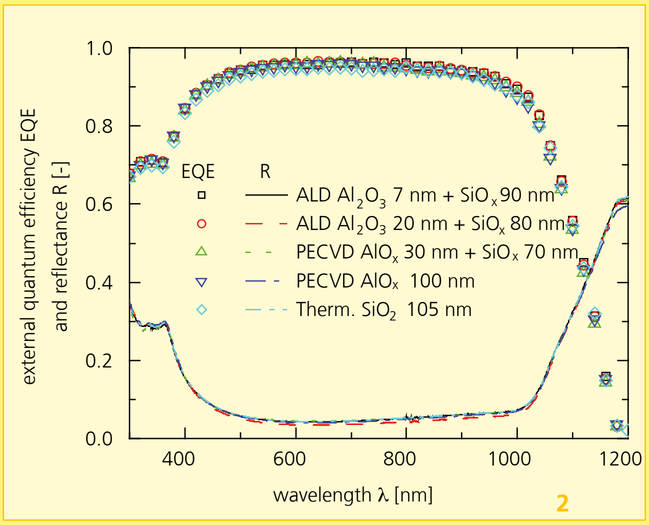


2

BACK-SURFACE PASSIVATION FOR SILICON SOLAR CELLS USING ALUMINIUM OXIDE

Surface passivation is a key process in the development of highly efficient crystalline silicon solar cells. Aluminium oxide layers are eminently suitable to passivate p-doped silicon. Following our development of a plasma-based high-rate deposition process, industrially relevant process technology to deposit such layers is available for the first time.

Jan Benick, Etienne Billot, Martin Hermle, **Marc Hofmann**, Daniel Kania, Jan Nekarda, Peter Olwal, Jochen Rentsch, Armin Richter, Pierre Saint-Cast, Stefan Glunz, Ralf Preu

1 Prototype of a PECVD coater for high-rate deposition of aluminium oxide layers for surface passivation of crystalline Si solar cells. A wafer holder can be seen in the foreground which offers room for 6 x 6 wafers (125 mm edge length). Alternatively, 25 wafers with an edge length of 156 mm can be coated.

2 External quantum efficiency and reflectance spectra for high-efficiency solar cells with ALD and PECVD aluminium oxide back-surface passivation in comparison to thermal SiO_2.

The production costs for crystalline Si solar cells have fallen drastically in recent years. To continue this trend, we are aiming to raise the solar cell efficiency, e.g. by the transition to solar cells with back-surface passivation.

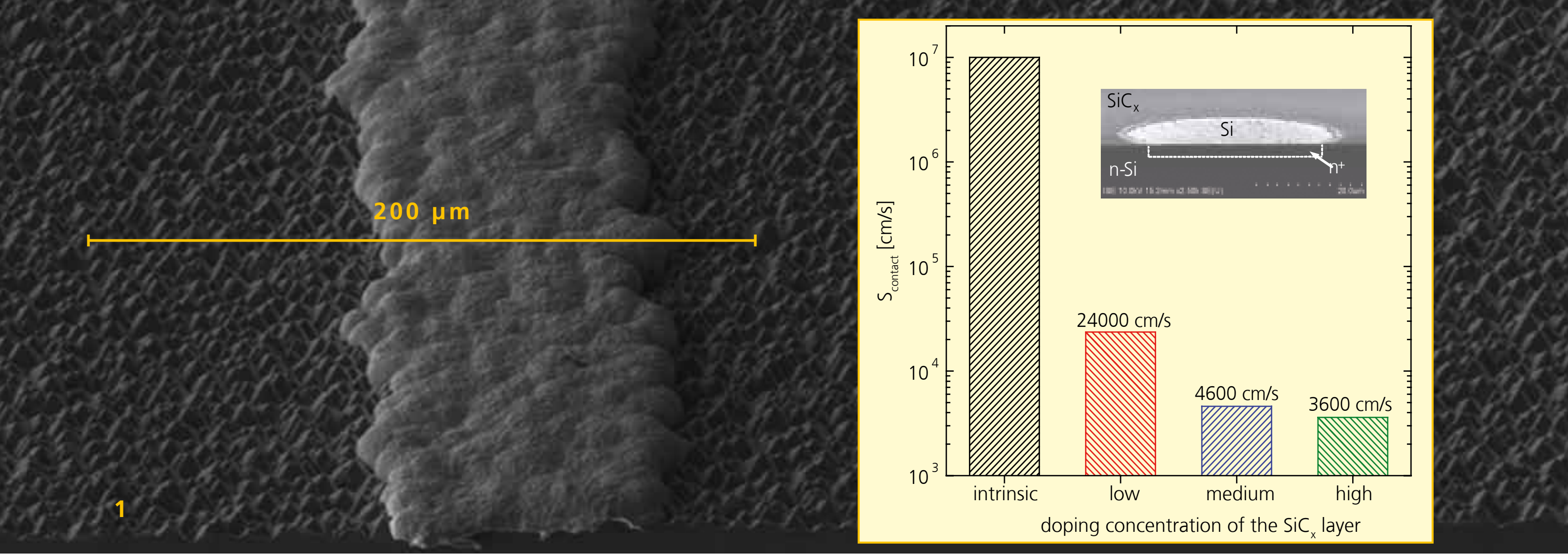
Various thin, usually dielectric layers are suitable candidates to passivate the back surface of solar cells: silicon nitride, silicon oxide, amorphous silicon or aluminium oxide. For introduction of the back-surface passivation layer to industrial solar cell production, not only the passivation quality but also optical properties and the stability in other production processes are decisive.

Aluminium oxide offers a particular advantage compared to the other alternatives. It provides localised negative charges, which lead to advantageous band bending in p-type silicon. Aluminium oxide layers can be deposited at low processing temperatures e.g. by atomic layer deposition (ALD) or plasma-enhanced chemical vapour deposition (PECVD). ALD is used in microelectronics to produce stoichiometric, almost ideal layers. However, the systems technology used is unsuitable for photovoltaics, so work is proceeding at present on PV-compatible systems.

For PECVD, we have succeeded for the first time in developing a process which allows strongly passivating aluminium oxide layers to be deposited dynamically with very high rates (~80 nm/min) over large areas. We carried out the development on a modified SiNA system from the Roth & Rau company.

Both processing approaches were compared using high-efficiency cell structures at Fraunhofer ISE, and showed very good results with efficiency values of 21.3 % (7 nm ALD-AlO_x + 90 nm PECVD-SiO_x) and 21.5 % (100 nm PECVD-AlO_x). Figure 1 shows the external quantum efficiencies and the reflectance spectra resulting from both approaches. The results for two other multi-layer stacks and thermally grown silicon dioxide (105 nm) are also shown. A similar, very good level is achieved with all of these coatings.

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



INDUSTRIAL IMPLEMENTATION OF HIGHLY EFFICIENT N-TYPE SOLAR CELLS

In the laboratory, we have achieved efficiency values of up to 24 % with an n-type solar cell with a boron-diffused emitter on the front surface. Our next goal was to develop technology for industrial implementation of this concept. We obtained an efficiency value of 19.6 % on a large cell area with printed front contacts and a completely metallised back surface. With a novel concept for industrially applicable back-surface passivation, a combination of passivation layer deposition and laser process, we reached an efficiency of 22.4 % on a small area.

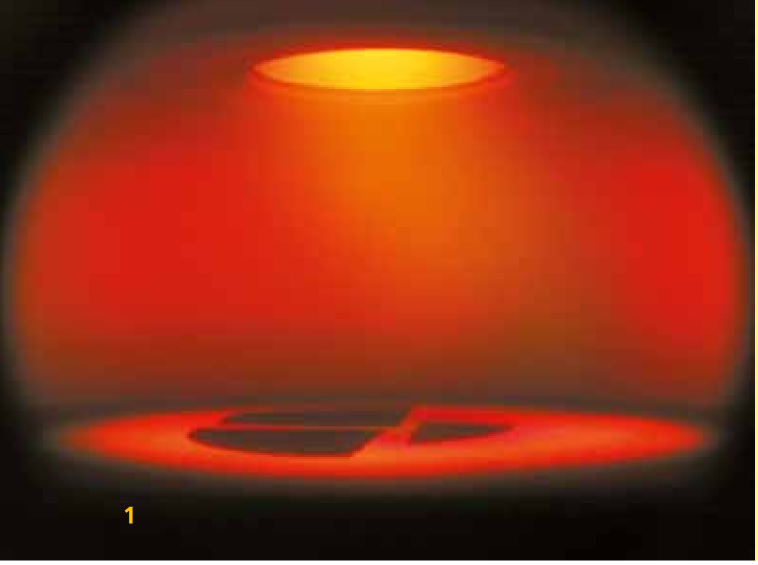
Jan Benick, **Martin Hermle**, Matthias Hörteis, Ulrich Jäger, Stefan Janz, Nicolas König, Antonio Leimenstoll, Michael Rauer, Armin Richter, Elisabeth Schäffer, Felix Schätzle, Christian Schmiga, Sonja Seitz, Dominik Suwito, Karin Zimmermann, Stefan Glunz

Due to continuous optimisation of solar cell processes and improvement of the efficiency, increasing attention is being paid to the material quality of the substrate. n-type silicon has clear advantages compared to the p-type silicon which has been used to date. The challenge now is to produce a high-quality p-doped emitter. Various concepts have already been investigated. For back-junction solar cells, the use of screen-printed and subsequently alloyed aluminium emitters is the simplest method. We were able to achieve efficiency values up to 20.1 % on small areas with this concept. Emitters of yet better quality can be obtained by boron diffusion. In our clean room, we produced an n-type solar cell with a boron-diffused emitter and photolithographically prepared contact openings which had an efficiency value of 23.9 %. However, photo-lithographic processes cannot be implemented industrially.

By contrast, firing metal seed layers through passivation layers and subsequent electro-plating is an approach which can be implemented industrially and is already used for p-type solar cells. With a specially developed metallic ink, we have now succeeded in contacting high-resistance boron emitters, whereby specific contact resistances on the order of 1 mΩcm² were achieved. These emitters can be excellently passivated with a simple layer sequence of Al_2O_3 and SiN_x, so that emitter saturation currents of clearly less than 50 fA/cm² after contact firing can be achieved. To estimate the potential, simple solar cells were produced with a diffused back surface field and back-surface metallisation over the entire area. With them, efficiency values of up to 20.5 % could be achieved for small cell areas. The achieved fill factor exceeding 81 % is note-worthy. When the concept was implemented for large cell areas, an efficiency value of 19.6 % was achieved. This solar cell is now mainly limited by the non-passivated back surface.

1 Front surface of an n-type solar cell covered with random pyramids, and a printed and electro-plated contact finger; Graph: Measured recombination rates for the PassDop contact as a function of the dopant concentration of the SiC layer.

With the development of the so-called PassDop process, we were able to take a major step toward the achievement of highest efficiency values. The PassDop layer which is used here enables excellent passivation of the n-type back surface on the one hand, while on the other hand, it contains dopants which can be introduced in a laser process during the local opening of the back-surface passivation layer for contacting, whereby a local back surface field is created below the contacts. In addition, the layer is also suitable as an optical reflector, so that the internal reflection is also very high. N-type solar cells on small areas with this newly developed back surface reached efficiency values of up to 22.4 % and an open circuit voltage exceeding 700 mV. The average for more than 75 solar cells was 22.2 %, which demonstrates the reproducibility and homogeneity of the process.



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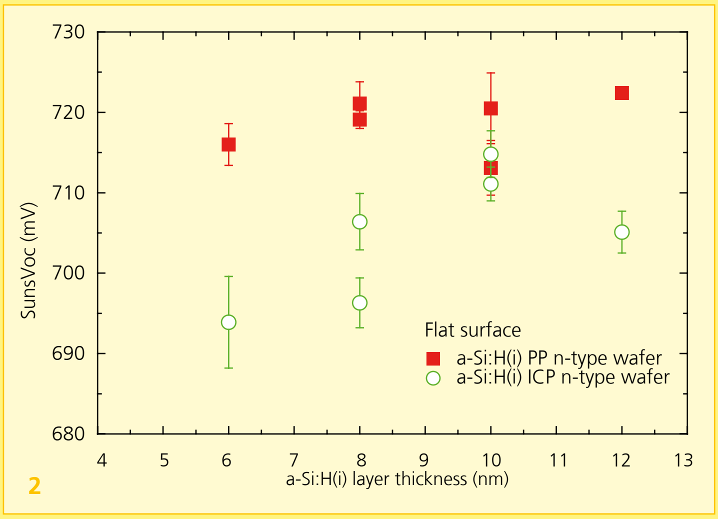


2

HIGHLY EFFICIENT SILICON SOLAR CELLS WITH HETEROJUNCTIONS

Effective reduction of surface recombination is a basic pre-condition for achieving highest efficiency values in Si solar cells. Particularly good passivation can be achieved by the use of amorphous silicon. If the layers on the front and back surfaces are doped in addition, very efficient solar cells can be produced, so-called amorphous-crystalline Si heterojunction solar cells.

Martin Bivour, Lena Breitenstein, Ines Druschke, **Martin Hermle**, Nicolas König, Christoph Meinhard, Damian Pysch, Christian Reichel, Kurt-Ulrich Ritzau, Christian Schetter, Sonja Seitz, Harald Steidl, Karin Zimmermann, Stefan Glunz

Highly efficient amorphous-crystalline Si heterojunction solar cells (a-Si/c-Si) are in the focus of current solar cell research due to their high efficiency potential. Very high voltages can be reached due to the effective surface passivation by the amorphous Si layers. The amorphous layers are usually deposited by plasma-enhanced chemical vapour deposition (PECVD). At Fraunhofer ISE, we have a plasma cluster facility available, with which we can deposit different layers sequentially in different chambers. In addition to the classic and widespread parallel plate (PP) configuration, we also have access to a plasma source with inductively coupled plasma (ICP). Excellent results concerning the passivation of Si wafers were reached with both plasma sources (fig. 2). However, a significantly lower deposition rate can be selected with the ICP source, which allows us to control the deposition better and also to modify it.

The variation of the dopant concentration within a 10 nm thin emitter layer is mentioned here as an example. By changing the dopant concentration within the emitter layer, the passivation properties and the conductivity can be altered. Doping gradients of almost any form can be introduced and their influence on solar cell characteristics investigated. Initial experimental results indicate that a higher efficiency value can be obtained with a linear doping gradient than for the reference structure with a constant doping profile.

An inherent disadvantage of a-Si/c-Si heterojunction solar cells is the light absorbed in the front-surface amorphous emitter layer which cannot be converted to electricity. This reduces the possible short circuit current of the solar cell and limits its efficiency. In order to avoid this effect, the amorphous emitter can be positioned on the back of the solar cell. New optimisation possibilities concerning the doping and thickness of the amorphous layer result. A further advantage of this concept is that there is no need for the transparent conducting oxide (TCO) which is usually included, or the optimisation window for the TCO is very wide, as there is no need for lateral conductivity.

To passivate the front surface, well-known methods such as the use of a front-surface field or passivating dielectric layers can be applied, which allow higher short circuit currents. We were already able to achieve efficiency values of up to 19.6 % with such a structure.

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

1 *View into the plasma chamber at Fraunhofer ISE.*

2 *Maximum achievable voltages as a function of the a-Si:H(i) layer thickness, for different plasma sources (PP and ICP).*

LINE OPTIMISATION AND PROCESS TRANSFER

1 *Wet-chemical processing equipment of the Photovoltaic Technology Evaluation Centre (PV-TEC) in Freiburg.*

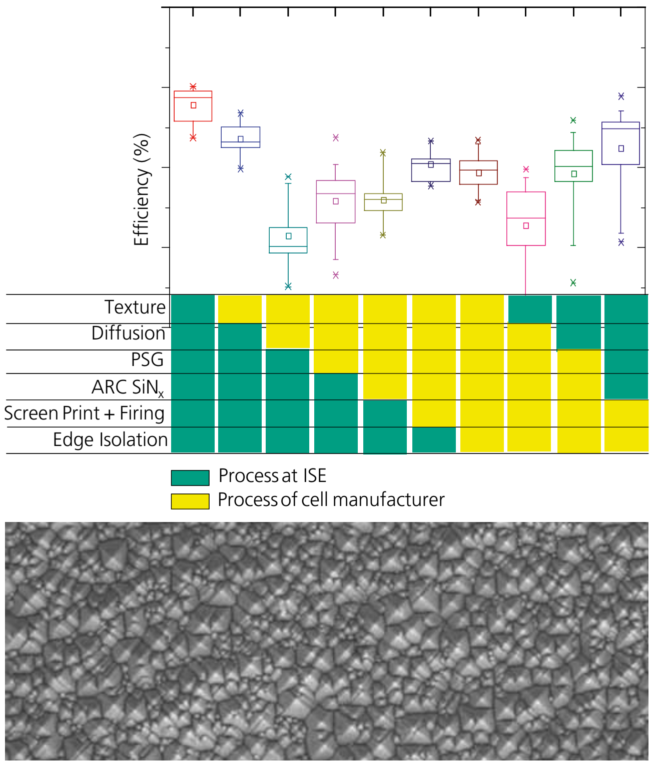
Improving the performance of a solar cell production line with regard to efficiency values and cost-saving represents one of the major challenges to solar cell manufacturers today. Fraunhofer ISE supports companies in the identification and improvement of performance-limiting processing steps and the introduction of novel, innovative processing sequences.

Udo Belledin, Katrin Birmann, Daniel Biro, Florian Clement, Denis Erath, Markus Glatthaar, Marc Hofmann, Norbert Kohn, Jan Nekarda, **Jochen Rentsch**, Andreas Wolf, Winfried Wolke, Martin Zimmer, Ralf Preu

The goal of our cooperation with each solar cell manufacturer is rapid process stabilisation and optimisation, and the identification of possibilities for future further development in processing technology and cell design. For line optimisation, initially the current status of each production step is determined. The investigations encompass not only the cell technology but also evaluation and characterisation of the Si material which is available to the solar cell manufacturer.

In the course of loss analyses, Si wafers are extracted successively after each relevant process step from the solar cell manufacturer's processing line or corresponding Si wafers which have been pre-processed at Fraunhofer ISE are introduced. The process steps which limit the efficiency value are identified by cross-comparison between the process step of the solar cell manufacturer and the corresponding reference process at PV-TEC, taking advantage of the extensive characterisation possibilities at Fraunhofer ISE. In further optimisation cycles, the identified process steps are then further developed on the basis of jointly defined process plans.

In addition to the evaluation and optimisation of complete process lines, Fraunhofer ISE also transfers individual processes or process sequences to existing lines belonging to solar cell manufacturers. In the past, for example, alkaline texturing for monocrystalline silicon was introduced to the production process by several solar cell manufacturers. The process transfer includes consultation services on the choice of suitable equipment, the transfer itself, the initial selection of promising process parameters and the determination of process parameters, which are usually specific to the particular equipment, for continuous operation by the client.



2 *Typical result of process cross-comparison with a solar cell manufacturer (above). Processing result of an alkaline texture on monocrystalline silicon (below).*

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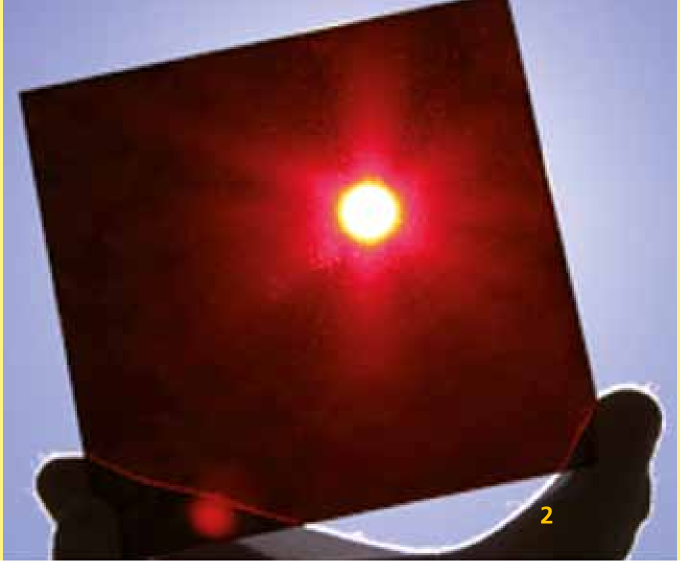

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10th ANNIVERSARY OF THE FRAUNHOFER ISE LABORATORY AND SERVICE CENTRE

In October 2000, the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen was officially opened, with support from the State Government of North Rhine-Westphalia. The goal was to create exemplary boundary conditions for cooperation between industrially relevant research, industry and users. After ten successful years, the Centre celebrated its 10th anniversary on 5th November, 2010 and was able to mark it by taking a new laboratory into operation.

1 *10th anniversary of Fraunhofer ISE Laboratory and Service Centre LSC in Gelsenkirchen: Prof. Eicke R. Weber (Institute Director of Fraunhofer ISE), Dr. Heinz Baues (Ministry for Climate Protection, Environmental Protection, Nature Conservation, Agriculture and Consumer Affairs in NRW), Dr. Dietmar Borchert (Director of LSC, Gelsenkirchen) – from left to right.*

2 *Light absorption by a glass pane coated with a thin film of amorphous silicon.*

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

The Fraunhofer ISE Laboratory and Service Centre LSC was established in close cooperation with industry with the aim of ensuring that research results immediately benefitted production. Research under conditions similar to industry and the direct implementation of laboratory results in production were the main objectives. "Production as in the factory, experimentation as in the laboratory" was the motto for the first few years. To this purpose, the first pilot line of Fraunhofer ISE to produce multicrystalline solar cells in industrial formats was commissioned in Gelsenkirchen.

During the first few years, the focus was on technological support and material investigations for the PV industry in North Rhine-Westphalia. Later, the services expanded to include material evaluation of multicrystalline silicon, "trouble-shooting" for operating production lines, the optimisation of continuous process lines and the establishment of special measurement technology for solar cells. The portfolio comprises the FAKIR system for rapid measurement of sheet resistance, a simple system to detect shunts in monocrystalline or multicrystalline Si solar cells, instrumentation to measure the spectral response of single-junction and tandem cells and a system to determine the defect density in amorphous silicon. Further activities in recent years include the characterisation and development of passivation layers for multicrystalline Si solar cells, as well as consulting and training.

The 10th anniversary was also accompanied by thematic expansion and the addition of new facilities at Fraunhofer LSC in Gelsenkirchen. A new technological laboratory with a floor area of around 400 m^2 was taken into operation to address the new key subjects of large-area silicon heterojunction solar cells and silicon thin-film solar cells. This expansion of the capacity in Gelsenkirchen is a response to the rapid development of the photovoltaic market in the thin-film sector and enquiries from the industry.

To develop both technological sectors further, a three-chamber coater was purchased as initial equipment for the new laboratory. This allows doped and undoped amorphous (fig. 2) and microcrystalline Si layers to be deposited by plasma-enhanced chemical vapour deposition (PECVD) over an area of 40 x 40 cm^2. Based on an existing fundamental process, a-Si/µc-Si and a-Si stack solar cells will be developed in pilot format.

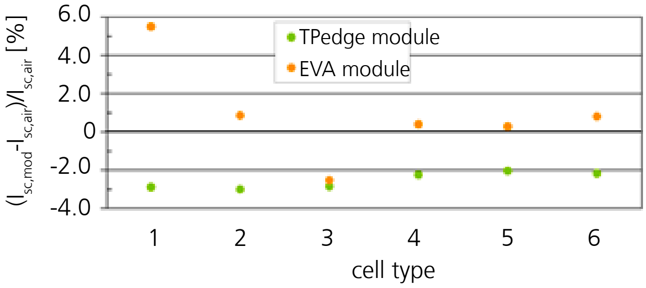
TPedge: COST REDUCTION BY EDGE-SEALED SOLAR MODULES

In conventional modules, the solar cells are laminated between the front glass cover, encapsulation material and the back polymer film. In order to lower material and processing costs significantly, Fraunhofer ISE has cooperated with Bystronic Lenhardt and Schmid Technology Systems to develop an edge-sealed solar module (fig. 1). The module concept dispenses with encapsulation material and has the cells mounted within an air-filled gap between two glass panes instead.

Ingrid Hädrich, Max Mittag, Harry Wirth

One research focus in the "TPedge" project is the analysis and optimisation of the performance and yield properties of module encapsulation. Optical and thermal effects in the module configuration are studied. Primarily the optical coupling of light through the various module layers was investigated in detail for the TPedge module in comparison to standard encapsulation with ethylene vinyl acetate (EVA). Whereas the solar cells in a reference module configuration are sandwiched between two layers of EVA behind a glass pane which is anti-reflectively (AR) coated on one surface, the cells in a TPedge module are surrounded by air behind a glass pane which is AR-coated on both surfaces. Optical edge effects were excluded for the analysis. By spectrally characterising the materials and combining the results with calculation models, we are able to determine the individual optical gains and losses caused by the encapsulation. A direct comparison of both module concepts for different cell types before and after encapsulation in the module demonstrated that primarily the quality of the cell coating and texture and the spectral response distribution have a clear effect on the change in performance of the cell in the module. Commercial cells with a high-quality texture can achieve similar or equal performance in the TPedge module to the reference configuration. Furthermore, cells with a high spectral response for short-wavelength light are disadvantaged by encapsulation in EVA, as this absorbs some of the light which is relevant for the cell's output power. This effect concerns cell technologies such as selective emitter cells which are currently entering the market.

1 *TPedge module with an area of 950 x 750 mm².*



2 *Percentage change in the short circuit current (I_{sc}) due to encapsulation in the new TPedge module and in a standard, EVA-encapsulated module.*

In addition to the performance and yield properties, we have addressed questions of reliability early in the TPedge development, guided by the specifications of IEC 61215. Resistance to hail impact and mechanical loads over the module area were successfully proven for a 20-cell module with a surface area of 950 x 750 mm².

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

ELECTRICITY FROM SUNLIGHT

ALTERNATIVE PHOTOVOLTAIC TECHNOLOGY

Complementing the work on silicon photovoltaics (see p. 52), our research and development on solar cells also extends to 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 extra-terrestrial applications, we are concentrating on radiation-resistant, multi-junction cells (triple to sextuple) and their special applications on extra-terrestrial planets. Cells with a low mass are important for space applications. 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 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

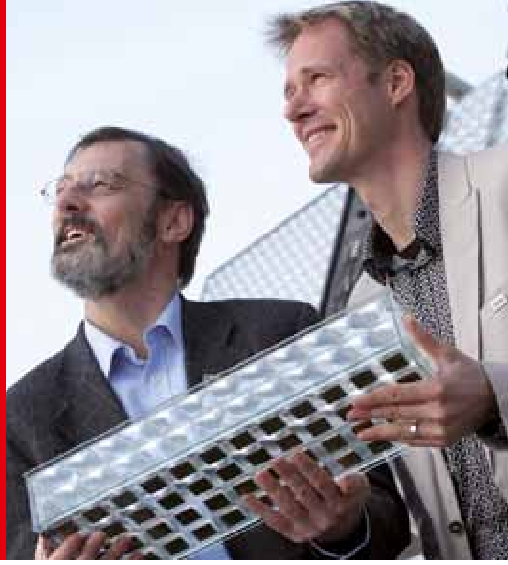
The technology for dye solar cells has developed well beyond the laboratory scale over the last few years. We were able to demonstrate that modules of dye solar cells can be produced with industrially relevant technology such as screen-printing and new sealing technology. The possibility for implementing design aspects was demonstrated in prototypes. The module durability is being tested in the laboratory and outdoors. In addition to the development of cell and production concepts, work is concentrating on scaling up dye solar modules for application in the architectural sector.

Organic solar cells

Organic solar cells are particularly attractive due to the anticipated low production costs. High mechanical flexibility will open up new application fields for photovoltaics in future. We are developing new cell structures which can be produced from cost-effective materials with efficient processes. The goal of these developments is production in a roll-to-roll process. We were able to produce 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. We are now able to achieve cell efficiency values of 5.4 %. 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 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 the spin-off company, Concentrix Solar GmbH.

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 dividing 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.

Dr Andreas Bett (left) and Dr Frank Dimroth (right) were awarded several prizes in 2010 for their research work on III-V multijunction solar cells for concentrator modules. In 2009, they and their team achieved an efficiency value of 41.1 percent for these extremely efficient solar cells (see article on p. 80). This record-breaking value was recognised in 2010 with the Joseph von Fraunhofer Prize, among others.

CONTACTS

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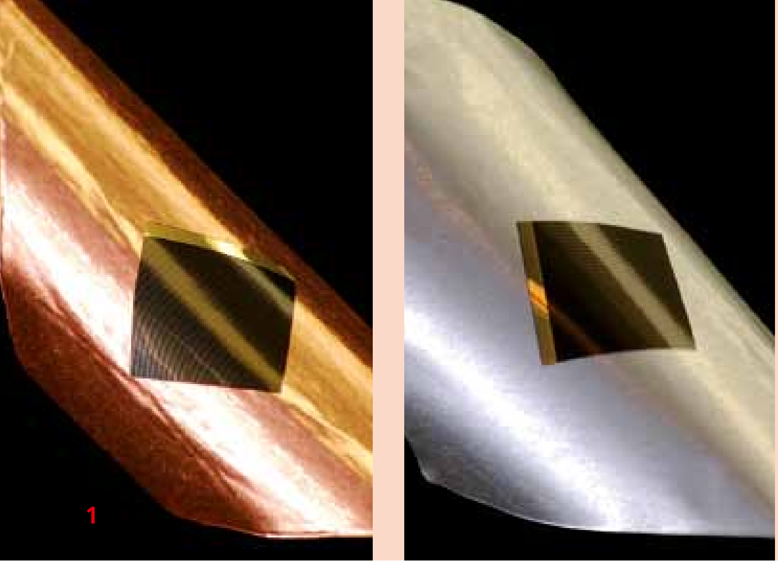

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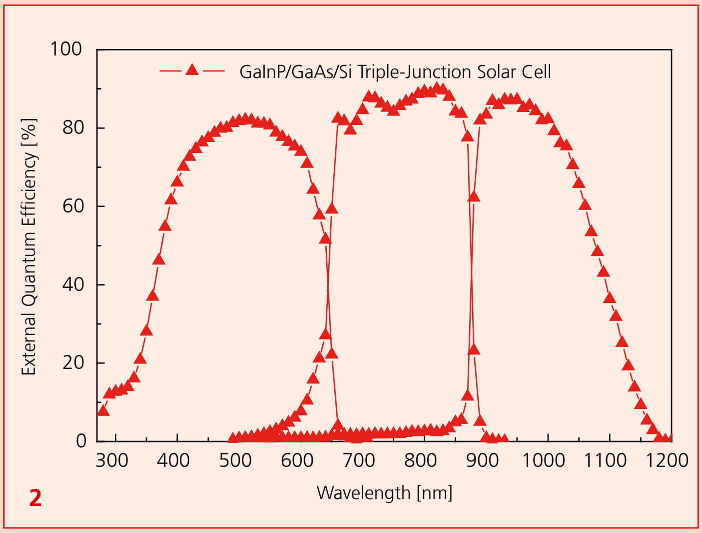


2

ULTRA-THIN MULTIJUNCTION SOLAR CELLS OF III-V COMPOUND SEMICONDUCTORS

At Fraunhofer ISE, we have developed concentrator solar cells of III-V semiconductors with efficiency values of up to 41.1 %. These complex devices are also used in space to generate electricity for satellites. We are now developing multijunction solar cells of the next generation, which are only 10 µm thin. With our processes, expensive substrates can be recycled, costs are reduced, and light and flexible solar cells can be realised for space applications.

Frank Dimroth, Karen Dreyer, Stephanie Essig, Elvira Fehrenbacher, Tobias Gandy, Stefan Glunz, Martin Hermle, Vera Klinger, Ranka Koch, Harald Lautenschlager, Toni Leimenstoll, Eduard Oliva, Michael Schachtner, Felix Schätzle, Manuela Scheer, Gerald Siefer, Katrin Wagner, Andreas Wekkeli, Andreas Bett

III-V multijunction solar cells are very efficient but are also expensive in comparison to conventional Si solar cells. Therefore, they are primarily used in space or in terrestrial PV concentrator systems, in which only a small solar cell area is required. Here, the III-V solar cells are already competitive today due to their high efficiency. A significant share of the cost is caused by the 150–300 µm thick substrate of extremely pure Ge or GaAs. This serves as a base for growth of the many semiconductor layers which absorb light in the solar cell and convert it to electricity. We are working on process technologies in which the III-V semiconductor layers, with a thickness of only 10 µm, are separated from the substrate. The substrate can then be reused for further film growth. This significantly reduces the consumption of rare and expensive materials such as Ge or GaAs.

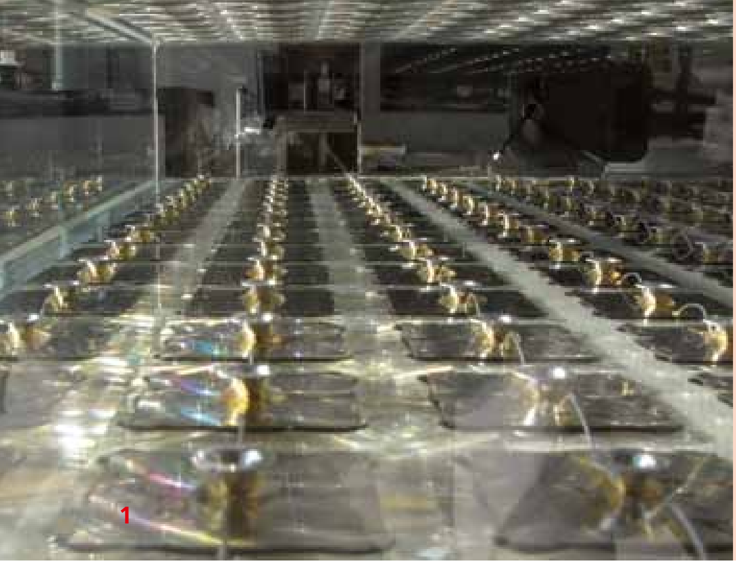
1 *10 µm thin multijunction solar cells of the next generation.*

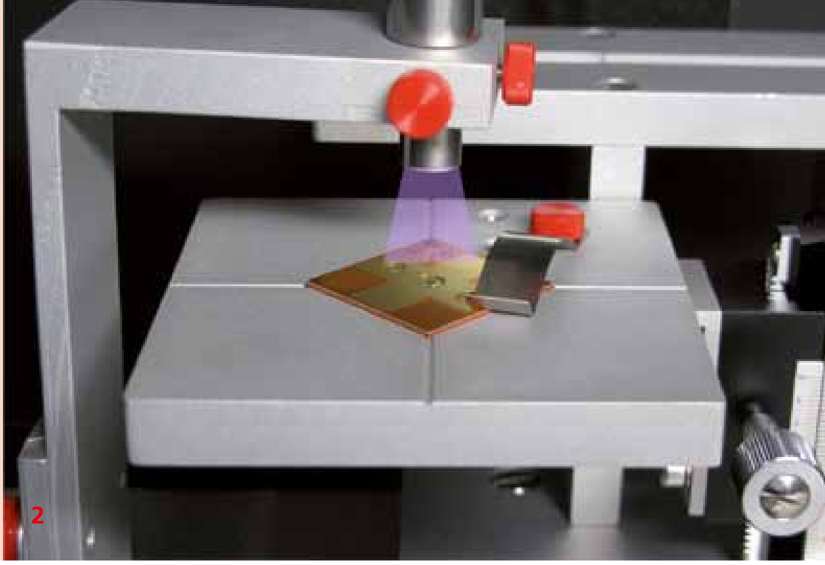
2 *External quantum efficiency of the first GaInP/GaAs/Si triple solar cell, which was produced by wafer-bonding a 6 µm thin tandem cell onto a Si solar cell.*

Furthermore, these thin multijunction solar cells offer advantages for space applications. Flexible and larger solar modules become feasible, which can be rolled up like foil (fig. 1). The thin cells reduce the mass of the satellite and lower the costs for transport into space. Together with the AZUR Space Solar Power GmbH company in Heilbronn, we are working on such concepts for the future, developing manufacturing processes and testing the ultra-thin multijunction solar cells under the harsh environmental conditions in space.

The separation techniques can also be used to transfer III-V multijunction solar cells onto other substrates. Completely new devices with improved properties can arise in this way. We have developed the first solar cells in which a GaInP/GaAs tandem solar cell is separated from the GaAs substrate and transferred to a Si solar cell. We apply the so-called "wafer-bonding" process to do so. The external quantum efficiency of the first triple-junction solar cell on Si is shown in figure 2. The cell with an area of 5.5 mm^2 reaches an efficiency value of 23.6 % under 48-fold concentrated sunlight. We are working on developing this concept further and increasing the efficiency values. In this way, we aim to combine the high efficiency of III-V multijunction solar cells in future with the widespread availability and low cost of Si solar cells. To this purpose, we are setting up a new laboratory for wafer-bonding.

This work is supported by the German Federal Ministry of Education and Research (BMBF) and the European Space Agency (ESA-ESTEC).





CONTEC – CONCENTRATOR TECHNOLOGY & EVALUATION CENTER

In ConTEC, we are working on the next generation of highly efficient concentrator modules. We are developing and optimising automated manufacturing processes which can be transferred directly to commercial production. As the high energy input of concentrated solar radiation presents a particular challenge, another focus of our work is investigation of the modules and components with regard to reliability.

Theo Bonnet, Armin Bösch, Alexander Dilger, Tobias Dörsam, Fabian Eltermann, Henning Helmers, Joachim Jaus, Felix Jetter, Kerstin Röder, Fatih Sabuncuoglu, Gerald Siefer, Sandor Stecklum, Patrick Uhlig, Michael Passig, Gerhard Peharz, **Maike Wiesenfarth**, Oliver Wolf, Christopher Zuckschwerdt, Andreas Bett

ConTEC is equipped with rapid and accurate production facilities like those which are also used for industrial manufacturing. Currently we are developing an automated production process for solar cell assemblies which are equipped with secondary optics. The solar cell assemblies, including the optics, are then positioned with great precision on a glass base plate. Figure 1 shows a complete base plate with solar cell assemblies and secondary optics in a FLATCON® module. In this example, the secondary optics has a funnel-shaped configuration and a reflective surface. The additional component widens the acceptance angle of the concentrator module, which increases the annual energy yield. New production concepts and new tools were developed to manufacture the modules. The image recognition of the automatic processes was adapted as the specifications became more stringent due to the additional optics. We have produced base plates for our industrial clients which correspond to a power of several kWp. The completed modules are now being tested in the field.

1 *Interior view of a FLATCON® module with solar cell assemblies and funnel-shaped secondary optics.*

2 *Test chamber for accelerated aging by UV radiation.*

Another main subject for ConTEC is the investigation of ageing effects in concentrator modules and module components and developments to minimise these. Due to the extremely high energy input at times of more than 100 W/cm^2 onto very small areas, thermal management is decisive for reliable and durable modules. In the design phase, we carry out thermal and thermo-mechanical simulations, which are compared with results of outdoor measurements. Accelerated aging tests then follow for investigation of the long-term stability. The test conditions are adapted to the module parameters which occur in real operation, and then increased by physically justifiable factors to accelerate the aging.

The load imposed on components by UV radiation presents a particular challenge to concentrator modules, as high UV doses are generated by the optical concentration. We thus carry out separate investigations of concentrator solar cells and optical materials, using test equipment we have set up for this purpose (fig. 2). The samples can be irradiated with UVA radiation with up to 6000 times the energy of the terrestrial solar spectrum (with reference to AM 1.5d, ASTM G173-03).

Our work in ConTEC is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU), the Deutsche Bundesstiftung Umwelt (DBU), the European Commission, Concentrix Solar, Zenith Solar and other industrial partners.


1

SCALING UP DYE AND ORGANIC SOLAR CELLS

Scaling up dye and organic solar cells is accompanied by many new scientific and technological questions, which are being intensively investigated at Fraunhofer ISE.

Henning Brandt, Katarzyna Bialecka, Katrine Flarup-Jensen, **Andreas Hinsch**, Ramiro Loayza Aguirre, Hans-Frieder Schleiermacher, Welmoed Veurman, **Uli Würfel, Birger Zimmermann**, Stefan Glunz

1 *The first completely filled prototype of a 60 cm x 100 cm dye solar module, which was produced at Fraunhofer ISE for application in architectural glazing.*

Dye solar cells are electrochemical solar cells and function similarly to the primary process of photosynthesis. In principle, they can be produced very simply and are a good example for research and implementation of functionalised nano-materials. The highest solar efficiency value that has been achieved in the laboratory for dye solar cells is just on twelve percent.

A commercially very interesting business model for the application of dye solar modules is building-integrated photovoltaics (BIPV). The goal is thus to develop photovoltaically active architectural glazing, in which decorative aspects and ecological benefit can be ideally combined for little additional cost.

At Fraunhofer ISE, a module concept was developed for this application which closely approaches the specifications and fabrication methods of the glazing industry. The modules are produced completely in a multiple-step screen-printing process and are subsequently sealed with a thermal fusing process which offers long-term stability. Large-area module prototypes were produced in cooperation with project partners. Before dye solar modules can be produced in series for architectural glazing, exact control of the production steps is needed to guarantee a correspondingly high product lifetime. To achieve this, we are developing specific quality control methods for the materials and the production processes.

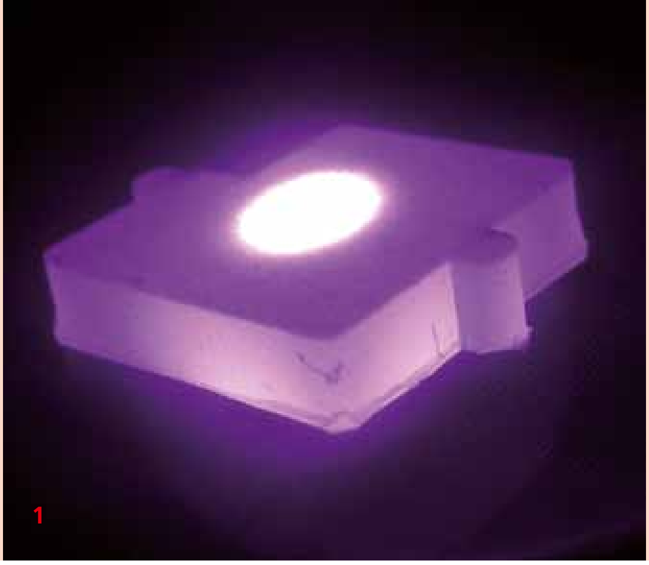
In extensive series of experiments, we have succeeded in producing functional prototypes of large-area dye solar modules on glass substrates. The feasibility of a screen-printed, integrated series connection for the modules has been demonstrated for the first time in the world for module areas of 60 cm x 100 cm. External connection of sub-modules is no longer necessary. This is an essential pre-requisite for cost-effective up-scaling.

Organic solar cells offer great potential for very cost-effective production. The reason is that organic solar cells can be produced in so-called roll-to-roll processes on endless flexible substrates at high rates. The production costs are determined almost entirely by the costs for the materials used, so that every saving in the materials reduces the module costs by the same factor.

One focus of our work is thus the replacement of the expensive indium tin oxide (ITO) superstrate. Various approaches are being pursued. One approach is the use of a < 10 nm thin silver film, which is embedded between semiconducting oxides. Organic solar cells of this type have already been produced on small areas with the same efficiency as cells with ITO electrodes. Furthermore, a substrate configuration based on a reflective, metallised film was developed, on which the solar cell is processed. The second electrode in this configuration consists of a transparent, conductive polymer layer. This in turn is either combined with a metal grid or contacted through to the back surface, where a second metal layer covering the whole area is located. Based on the substrate concept with the polymer/grid electrode, ITO-free flexible organic solar modules are already being produced at Fraunhofer ISE on areas of several square centimetres with coating processes that are compatible with roll-to-roll production. A further important aspect of upscaling is the structuring of different layers. We are working on processes which are adapted to the special properties of the individual layers and the corresponding quality specifications. One example is the contact resistance which arises in the Z circuit configuration. The next step is to transfer the very good laboratory results to a roll-to-roll coater. An industrially compatible coater is currently being acquired as a strategic investment.

2 *Preliminary coating tests using a production rotogravure press and dyes without a photovoltaic function. The tests served to characterise the positioning accuracy during printing on already existing structures, in order to determine the technical boundary conditions for new organic solar module concepts.*

The work is supported by the German Federal Ministry of Education and Research (BMBF), the State Ministry for the Environment in Baden-Württemberg and the European Commission.



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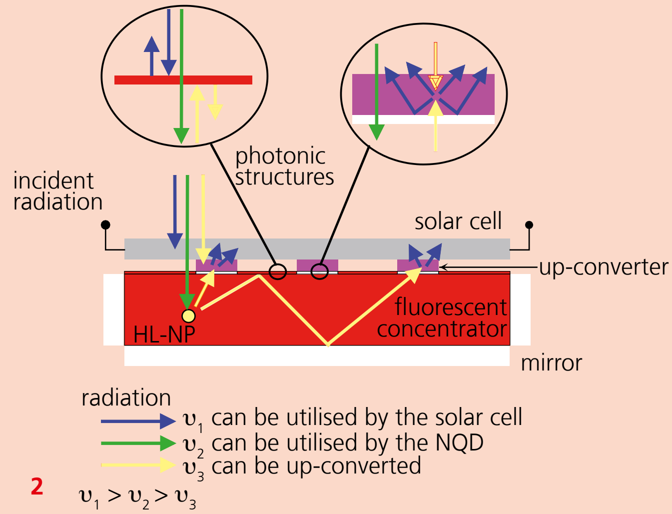


2

UP-CONVERSION – MAKING LOW-ENERGY PHOTONS USEFUL

Around 20 % of the incident solar radiation is lost because Si solar cells cannot use photons with energy lower than the silicon band gap. These photons can be made useful by up-conversion. In this process, at least two photons with too little energy are converted into a photon in the useful energy range. In order to increase the efficiency of this process, we are investigating several concepts: Combination with a second luminescent material allows the usable spectral range to be broadened considerably; combination with metal nanoparticles can increase the efficiency of the up-conversion process.

Stefan Fischer, **Jan Christoph Goldschmidt**, Martin Hermle, Barbara Herter, Heiko Steinkemper, Tim Rist, Stefan Glunz

Erbium is a very efficient material for up-conversion if it is embedded in suitable host crystals such as $NaYF_4$. With a sample of this type of material, which was produced by the University of Berne, Fraunhofer ISE has succeeded for the first time in demonstrating a measurable contribution to the short circuit current of a Si solar cell by excitation with a broad spectrum.

Erbium has the disadvantage that its absorption spectrum is only very narrow. The number of up-converted photons can thus be increased significantly if erbium is combined with a second luminescent material. This material should exhibit a broad absorption spectrum and emit within the absorption range of erbium. Luminescent semiconductor nanoparticles (NQD – nanocrystalline quantum dots), e.g. of lead selenide, are suitable candidates.

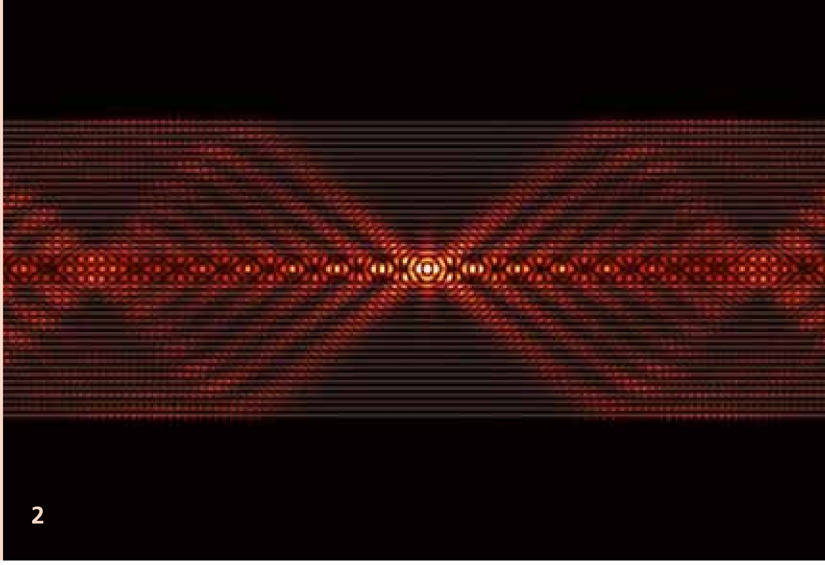
1 *Up-converter, which glows brightly in the visible range when illuminated with invisible infrared radiation.*

2 *Advanced system design for the combination of an up-converter with a second luminescent material.*

Figure 2 shows an advanced system design to implement such a concept. The up-converter is located behind a bifacial Si solar cell. The photons with energy below the band gap are transmitted through the solar cell. The second luminescent material (NQD) is integrated into a fluorescent concentrator. It concentrates the radiation onto the up-converter. This increases the efficiency of the up-conversion, because up-conversion is a non-linear process. Spectrally selective photonic structures ensure that light from the different spectral ranges is directed into that part of the system where it is used most efficiently. Together with our project partners, we are working on implementing and optimising a system containing all the described components.

A further approach is to exploit the plasmon resonance in metal nano-particles to increase the up-conversion efficiency. The plasmon resonance causes strong field amplification near metal nano-particles. This can be used to increase the up-conversion efficiency due to its non-linearity. In addition, the individual radiative transitions of the up-converter are affected. Initial simulations, which combine a rate equation model for up-conversion with Mie theory calculations by RWTH Aachen, demonstrate a clear increase in the up-conversion efficiency.

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



CONCENTRATING DIFFUSE LIGHT WITH FLUORESCENT CONCENTRATORS

Fluorescent concentrators can concentrate both direct solar radiation and diffuse light. They are particularly interesting for use indoors and also for building-integrated applications due to their aesthetics. Their efficiency must be increased for commercial applications. This is achieved with photonic structures which improve light-guiding. Special infrared-active semiconductor nano-particles extend the usable spectral range into the infrared.

Benedikt Bläsi, **Jan Christoph Goldschmidt**, Johannes Gutmann, Martin Hermle, Marius Peters, Janina Posdziech, Tim Rist, Stefan Glunz

The dyes in fluorescent concentrators absorb incident light in a certain spectral range. Shortly afterwards, they emit light in a narrow spectral band with longer wavelengths. Some of this light is guided by total internal reflection to the edges of the concentrators. The fraction of captured light can be increased by so-called spectrally selective photonic structures. They transmit the light in the absorption range and reflect the emitted light. As a result, almost all of the emitted light reaches the edges. An increase in the light-guiding efficiency of 20 % has been demonstrated experimentally. At present, complex multi-layer stacks are used as the photonic structures. These are still expensive to produce, so we are developing cost-effective alternatives. One possibility is the production of so-called opal films. They consist of monodisperse PMMA spheres of several 100 nm diameter, which undergo a self-organised process to form quasi-crystalline structures.

In order to further increase the light-guiding efficiency, we are also investigating incorporation of the dyes directly into the photonic structures (fig. 2). One approach is to integrate thin films which contain the dye into the multi-layer photonic stack. Another is to manufacture the described opal films of spheres which already contain dye molecules. In order to find optimal system designs, the properties of each system are investigated by the combination of various simulation tools. These include transfer matrix approaches, finite difference time domain (FDTD) and rigorous coupled wave analysis (RCWA).

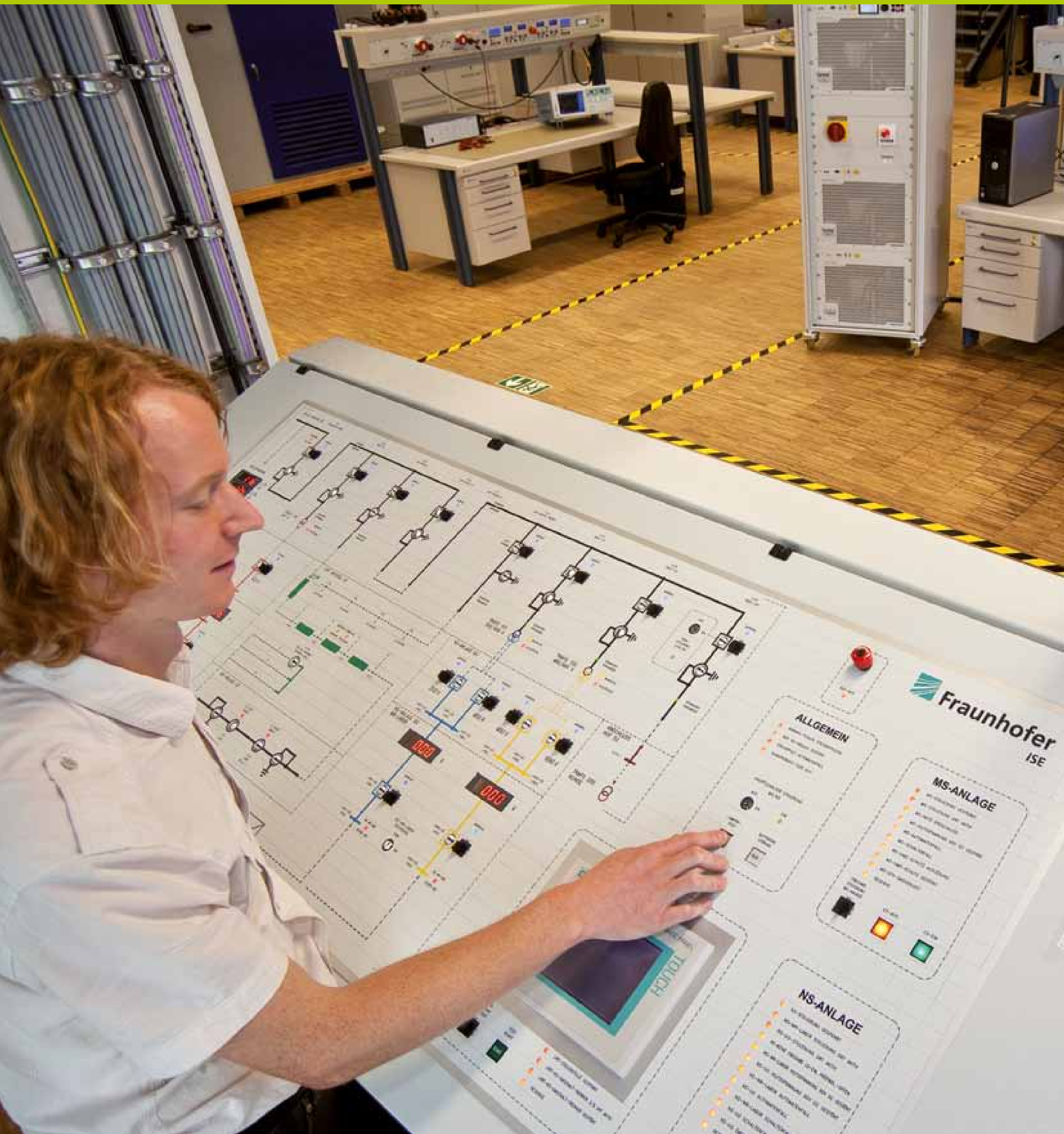
The organic dyes used feature high quantum efficiency for the absorption and emission processes. However, each one exploits only a narrow spectral band. Several fluorescent concentrators with different dyes are combined to cover a broader band of the solar spectrum. With such a combination and the use of spectrally matched solar cells, a very high system efficiency value of 6.9 % was achieved at Fraunhofer ISE. In their active range, the fluorescent concentrators guide more than 60 % of the incident radiation to the edges. The strongest limitation on the system efficiency is imposed by the fact that there are no organic dyes which are active in the infrared (IR) with a high quantum efficiency. We are thus cooperating with partners to develop fluorescent concentrators which are IR-active. Luminescent semiconductor nano-particles such as lead selenide or lead sulphide are used.

The work is supported by the Deutsche Forschungsgemeinschaft (DFG) and the Fraunhofer-Gesellschaft.

1 *Fluorescent concentrators doped with different dyes.*

2 *Efficient light-guiding within a photonic structure from an emitter (image centre) to the edges. The intensity distribution of the emitted light as obtained by FDTD simulation is shown.*

SUPPLYING POWER EFFICIENTLY



RENEWABLE POWER GENERATION

Around two billion people in rural areas, innumerable technical systems for telecommunications, environmental measurement technology or telematics, and four billion 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. Around 5 % of the photovoltaic modules sold world-wide are 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. We focus particularly on electric storage components such as batteries, which are found in almost all applications. This applies increasingly also for grid-connected energy systems, in which stationary or mobile storage units can dampen the fluctuations in electricity generated from wind or solar energy. Thus, we are working intensively on developing and optimising battery systems for stationary and mobile applications (electric vehicles). Our work concentrates on increasing the power range and storage capacity, improving operation management strategies and developing control systems for all common types of battery technology.

The number of grid-connected systems installed has increased enormously over the last few years. To maintain this market growth now that feed-in payments are decreasing, the costs for the systems technology must also be reduced continually. 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. 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.

We offer a wide range of services for quality control and operation monitoring of PV systems and characterisation of PV modules, which encompasses yield predictions, plant authorisation and monitoring of large systems and precision measurements of modules. Our photovoltaic calibration laboratories (CalLab PV Cells and CalLab PV Modules) are among the internationally leading laboratories in this field.

Regardless of whether photovoltaic, wind-energy, hydroelectric or combined heat and power plants are involved: In Germany alone already ten thousands of distributed generators feed their electricity into the distribution grids. In order to cope with the anticipated enormous penetration rates and 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 important role in this process.

In their plans to achieve the announced environmental goals, the German Federal government, industry and science attribute great significance to electromobility, based on vehicles that 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

From the control desk of the new megawatt laboratory at Fraunhofer ISE, we can carry out manual or automatic switching operations at the low-voltage and 20 kV medium-voltage levels. This is the basis for operating and testing large solar inverters up to a power of one megawatt.

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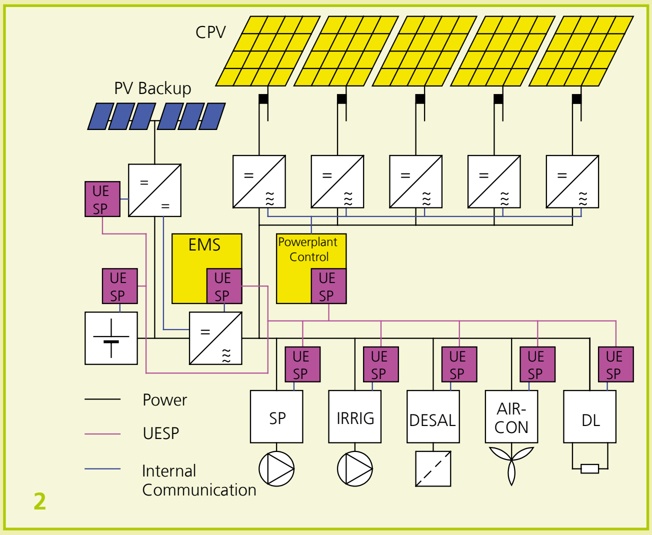


2

CPV OFF-GRID SYSTEM FOR WATER SUPPLY IN EGYPT

Within the EU-funded "NACIR" project, we have developed an autonomous system based on concentrator photovoltaics (CPV). It supplies electricity for water pumping, desalination and irrigation, and we installed it in Egypt. The core of the development work is an intelligent energy management system (EMS), which ensures maximum direct usage of the available solar energy. This reduces intermediate storage in batteries to a minimum and thus significantly lowers the costs for the storage units which must be installed.

Binod Prasad Koirala, Alexander Schies, **Matthias Vetter**, Jakob Wachtel, Joachim Went, Günther Ebert

Access to water resources for drinking and irrigation is becoming increasingly critical in many regions of the world, particularly in rural regions of arid countries with poor infrastructure. Not only pumping systems, but often also an adequate power supply is lacking. Therefore, diesel generators are often used, which are cheap to purchase but expensive to operate and maintain. By contrast, PV stand-alone systems are more cost-effective over the entire lifetime for most applications, despite their higher investment costs. One possibility to reduce the investment costs for water supply systems is to reduce the size or completely eliminate the electric storage unit by using the solar energy which is available during the day directly.

The pre-condition for this is an intelligent system design and a well-adapted energy management system. To provide this, we have developed a comprehensive library of models for a wide range of loads, generators, storage units and energy converters in the Dymola modelling environment. Systems are dimensioned, simulated and optimised using these models. This means that energy management algorithms can be developed and optimised in the course of simulation studies, before they are validated in the laboratories at Fraunhofer ISE. The algorithms developed in this way are then transferred to systems in the field, e.g. in Egypt.

For the "NACIR" project, we initially developed a priority-controlled algorithm, which switches loads on or off according to the currently available solar energy or adjusts them according to the solar energy supply. In this way, the available energy is supplied directly to the loads and the storage unit is bypassed. At present, a new algorithm to calculate weather forecasts is being tested in the laboratory. This serves to define a load schedule for the following day, and specially developed algorithms then optimise the priority ranking and energy utilisation. In this way, the system efficiency can be increased further. The universal energy supply protocol (UESP), which was developed at Fraunhofer ISE, was used as the communications infrastructure for the system. It allows communication with all components of the system, regardless of their manufacturer. With the UESP protocol, it should be possible to simply extend the system with the existing EMS, and in future, stand-alone systems could be constructed on a "plug and play" basis. Such cost-optimised, stand-alone PV systems help to electrify remote areas sustainably and cost-effectively. In addition to the development of optimised systems, knowledge transfer occurs in parallel to the field installations by special training for the people responsible on site.

1 *CPV stand-alone system in the El Natroon Wadi, 100 km north-west of Cairo, Egypt: Five CPV trackers, each with 6 kWp.*

2 *Schematic diagram of the NACIR CPV stand-alone system. Each component is connected via the Universal Energy Supply Protocol (UESP) with the energy management system (EMS).*

DEVELOPMENT OF TEST METHODS AND INVESTIGATION OF PV LAMPS

Fraunhofer ISE was commissioned by the "Gesellschaft für Technische Zusammenarbeit (GTZ)" and the World Bank/International Finance Corporation (IFC) to develop test methods for characterising photovoltaically powered lamps and to carry out extensive tests of such lamps. In total, more than 100 samples of 30 different lamp types were investigated and evaluated.

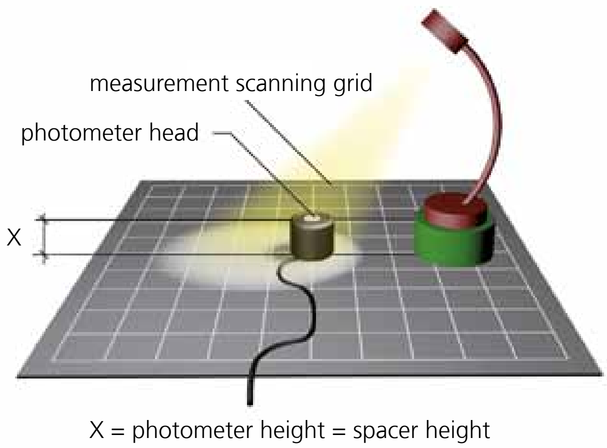
Georg Bopp, Stephan Lux, Markus Müller, **Norbert Pfanner**, Michael Strasser, Christian Wieczorek, Günther Ebert

Altogether 1.6 thousand million people do not have access today to a public electricity grid. Petroleum lamps are thus often used for lighting in rural areas. The operating costs for these lamps often represent the greatest expenditure for very poor households. An environmentally friendly and inexpensive alternative is offered by small, photovoltaically powered lamps. However, investigations have revealed that there are large differences in the quality of commercially available PV-powered lamps. In a first step, Fraunhofer ISE thus developed test methods to determine the quality of PV-powered lamps. These were specially adapted to the financial and technical possibilities of test laboratories in developing and threshold countries. The test methods encompassed the aspects of lighting utility, practicability and robustness. In the practicability test, the lighting duration, charging performance and handling are checked. The lamp robustness is investigated with drop and mechanical load tests of the electric connections and switches. A continuous test provides information about the long-term stability of the light sources used.

More than 30 different types of PV-powered lamps were investigated and evaluated according to the test methods developed in our lighting laboratory. In the course of the measurements and tests, the methods were refined and optimised with regard to applicability and costs in cooperation with an external Chinese laboratory (National Lighting Test Centre). The results of the investigations revealed in some cases considerable weaknesses concerning the electronics, component quality, compliance with specifications, mechanical construction, lighting quality and lifetime. The large scatter in results among the up to six investigated samples per lamp type was also notable.

1 *Main application for small photovoltaically powered lamps: Reading after sunset.*

2 *Two examples of the lamps tested at Fraunhofer ISE.*



3 ***Set-up developed at Fraunhofer ISE to test the illuminance of reading lamps inexpensively.***

The work was supported by the "Gesellschaft für Technische Zusammenarbeit (GTZ)" and the World Bank Group.

INTELLIGENT MARKETING OF ELECTRICITY FROM DISTRIBUTED ENERGY SOURCES

Distributed and renewable electricity generators must also be integrated in future into the European electricity markets and the operation management of public electricity grids. In a European research project, we have prepared solutions for intelligent marketing of electricity and other services for those generators which are relevant today and will be in the near future.

1 *Interior view of the CHP plant in Friesenheim, Germany. The plant belonging to badenova WÄRMEPLUS was one of the case studies in the EU-funded "MASSIG" project.*

Thomas Erge, Christian Sauer, Christof Wittwer, Günther Ebert

In the research project entitled "Market Access for Smaller Size Intelligent Electricity Generation (MASSIG)", we cooperated with project partners to investigate how electricity from distributed and environmentally friendly generators can be supplied and marketed in a liberalised electricity market according to demand and covering costs. The central question was: How can small and medium-sized electricity generators (up to several MW) enter large markets? The project team selected Denmark, Germany, Great Britain and Poland as examples of target countries. Taking account of the legal, regulatory and technical boundary conditions and specifications, the nationally specific market opportunities were analysed with profit and loss calculations, and measures for successful entry into the market were derived from the results. One fundamental result of the project is: Particularly when several regionally distributed electricity generators form a consortium and offer intelligent electricity products on the market, they can indeed compete successfully with large conventional suppliers. The key to success is to offer further services in addition to the pure supply of electricity. For example, grid operators require different types of so-called regulatory electricity to compensate for unplanned and short-term imbalances in the electricity grid, which they must procure via transparent markets and trading processes. Further examples of services include the limitation of peak loads in the electricity grid or measures to stabilise the voltage in local electricity grid sectors (e.g. by feeding in reactive power). Distributed and alternative electricity generators are also able to contribute such products and profit from them, if they are equipped with intelligent operations management.

badenova WÄRMEPLUS was one of the seven European project partners. The subsidiary of the regional utility, badenova, operates combined heat and power (CHP) plants and delivers heat and cooling power to thousands of customers in South-West Germany. Together with this industrial partner, a concept was prepared which allows the CHP plants to be operated profitably, even once the funding from the German law on combined heat and power generation has ended. The concrete implementation means that in future, badenova WÄRMEPLUS will not only sell electricity on the market, but also simultaneously offer regulatory electricity products for acquisition by grid operators. The project work identified very promising solutions for badenova WÄRMEPLUS. It became clear that electricity generation by cogeneration of heat and power can continue to be profitable under the current, more difficult conditions, if intelligent marketing strategies are implemented.

The project was supported by the European Commission within the "Intelligent Energy Europe" Programme. The project partners were badenova WÄRMEPLUS, EMD, EREC, Lodz University, Manchester University and Vienna University.

SMART ENERGY LAB FOR THERMAL AND ELECTRIC BUILDING ENERGY SYSTEMS

The integration of renewable electricity-generating technology demands energy-management concepts and solutions which start with the intelligently networking Smart Home of the future. The Smart Energy Lab at Fraunhofer ISE offers an ideal platform to develop and evaluate energy management solutions, including the incorporated information and communication technology.

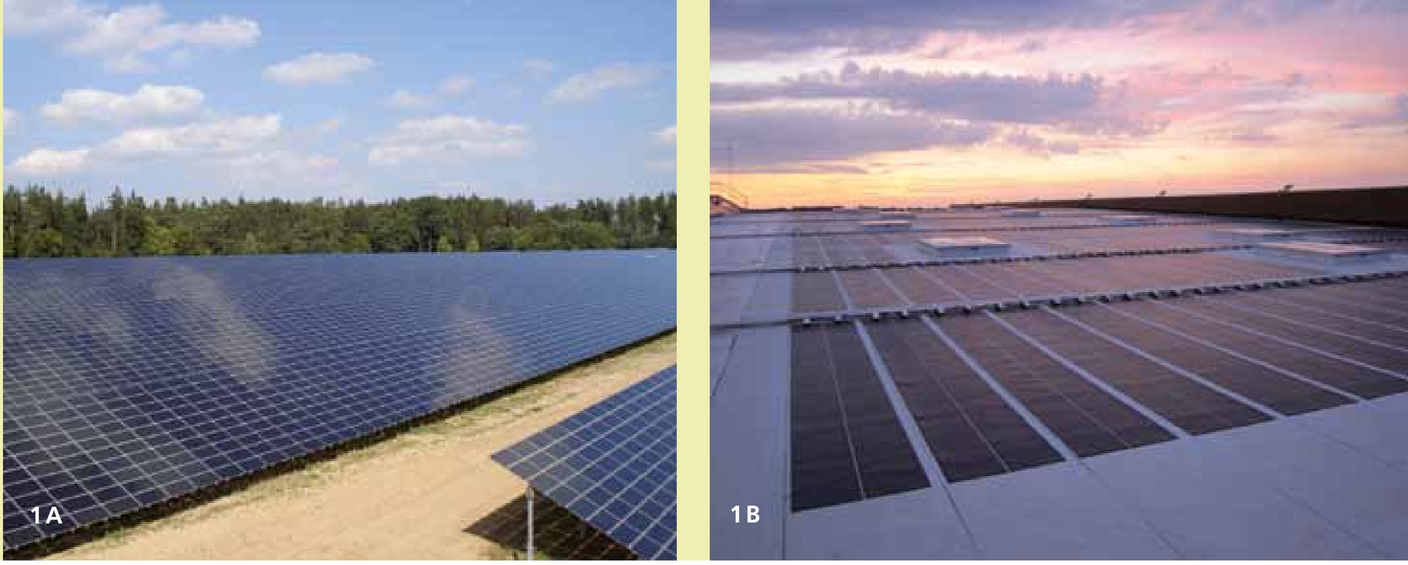
1 *Interior view of the Smart Energy Lab at Fraunhofer ISE.*

Dennis Freiberger, **Bernhard Wille-Haussmann**, Christof Wittwer, Günther Ebert

With its many years of experience in systems technology, Fraunhofer ISE is an ideal partner for intelligent energy systems in the distribution grid. In 2010, the institute took its modern Smart Energy Lab into operation. This test laboratory is equipped with efficient renewable electric and thermal generators and storage units for future residential buildings, large and small. With the capability to model and network all energy flows, the laboratory offers a unique platform to analyse, evaluate and develop Smart Homes and Smart Grid technology.

The Smart Energy Lab is equipped with a 5 kW combined heat and power plant (CHP) which can operate autonomously, a 2 m³ stratified buffer tank, a photovoltaic simulator, several photovoltaic inverters and diverse stand-alone inverters, a lithium-ion storage battery (7.5 kWh), a lead-acid battery bank (15 kWh) and charging infrastructure for electric vehicles. On the IT side, all components are integrated into the building circuit via interfaces and bus systems (Industrial Ethernet). Energy management and feedback systems are implemented with efficient embedded systems, which can be adapted to any client-specific specifications. Powerful simulation computers, which support model-based and "hardware in the loop" operation, are also available. Thus, any required dynamic scenarios for consumption and generation in the domestic context can be imposed.

The Smart Energy Lab supports manufacturers and operators of energy systems and control systems with diverse services. The main emphasis is on powerful, reliable and energy-efficient integration of all components into an intelligently connected building energy system. The services offered include evaluation of the integration of thermal and electric components in a system, which is achieved by simulation, optimisation, operation management and systems control. This also includes the simulation of economic scenarios for "pooling" building energy systems and virtual power stations. Furthermore, we offer functionality and communications testing of smart metering and energy management systems (Smart Energy Gateways) which transcend trade sector boundaries. Beyond these services, centralised and mobile metering systems can be developed and tested with a charging infrastructure for electric vehicles, while in the software sector, communications implementation and conformity tests of customer equipment are offered (e.g. SML, IEC 61850, M-bus). The service portfolio is rounded out by efficiency analyses of energy management and generation systems.



PRECISE POWER MEASUREMENTS OF PV GENERATORS IN THE FIELD

On-site measurements of the power generated by PV arrays present a reliable method to check the real performance of the solar modules with a representative random sample, without having to dismount modules. Accurate measurements with a measurement uncertainty of less than 5 % are possible, as long as the measurements are carried out by experts, and the measurement equipment and the procedures to extrapolate to standard test conditions are chosen correctly.

Daniela Dirnberger, Klaus Kiefer, Frank Neuberger, Andreas Steinhüser, Harry Wirth

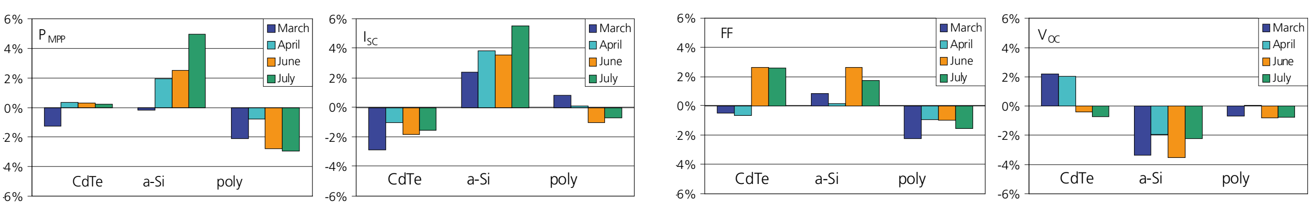
The output power of modules in a PV system is determined in three steps: Measurement of the current-voltage characteristics under the prevailing meteorological conditions, correction of these measured values to standard test conditions and, if necessary, consideration of external effects such as module soiling or electric cable losses.

The current-voltage characteristics are recorded for individual strings and sub-generators, i.e. for units of connected modules ranging from 5 to 100 kW_p. The module temperature and the irradiance are also measured simultaneously. The measured power is extrapolated to standard test conditions by the use of characteristic parameters which describe the radiation and temperature dependence of the modules.

1 On-site measurements of current-voltage characteristic curves represent a reliable method for quality control, not only for free-standing systems (A, Höttingen, 4.4 MWp) but also roof-mounted systems (B, Cambrai/Lidl, 1 MWp).

The total uncertainty for determining the power is influenced by several factors. Firstly, the uncertainty of the irradiation measurements is decisive, which is why Fraunhofer ISE uses a primary-calibrated reference cell (± 0.5 %). The second important influence is the deviation of the real from the standard test conditions: The larger the deviation, the greater is the uncertainty due to the extrapolation. Useful measurements of characteristic curves can thus only be carried out for sufficiently high solar irradiation values under a clear blue sky. Thirdly, exact results can be obtained only with carefully determined module parameters. It is advisable to carry out the necessary measurements on one module as a representative of the investigated module type.

As a result, uncertainty values between 3 % and 5 % can be achieved if the criteria discussed above are observed and the measurements are carried out by experts. Figure 2 illustrates that on-site measurements represent a good alternative to laboratory measurements for various types of technology.



2 Comparison of field measurements with measurements in CalLab PV Modules at Fraunhofer ISE confirms the accuracy of the measurement and correction procedures for different types of cell technology.

1 A

1 B

PV POWER PLANTS – STABLE PERFORMANCE OVER MANY YEARS

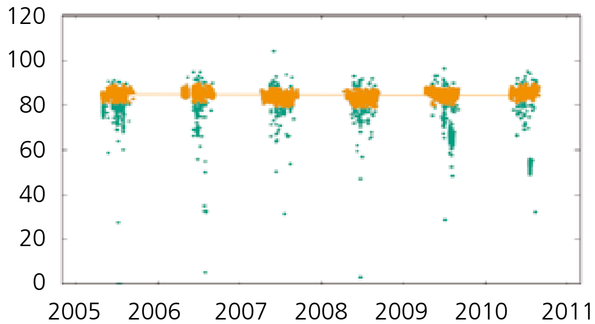
Fraunhofer ISE has experience with monitoring PV systems which dates back to 1990 and the start of the 1000 Roofs Programme. Today, more than 200 systems with a total power of 75 MW are monitored in detail. Experience from long-term monitoring demonstrates that monocrystalline and polycrystalline modules generate power reliably over many years and that no systematic degradation can be detected.

Daniela Dirnberger, Wolfgang Heydenreich, **Klaus Kiefer**, Anselm Kröger-Vodde, Björn Müller, Harry Wirth

The Fraunhofer ISE monitoring system encompasses the exact measurement of solar radiation with calibrated sensors and the generated electricity. The module and ambient temperatures are also recorded. In addition, the current and voltage for a reference sector of the solar generator is measured, which allows the solar generator efficiency and the inverter efficiency to be calculated. Measurements made at 1 s intervals are recorded as 5-minute averages.

In order to detect long-term changes in the performance ratio or the solar generator efficiency, influences such as different irradiation levels and temperatures must be eliminated. For this study, the 5-minute averages which were measured under typical operating conditions were extracted (green points in fig. 2). These conditions correspond to irradiance values between 800 Wm^{-2} and 1000 Wm^{-2}, and module temperatures of 40–45 °C. After outliers had been removed, a linear regression was applied, which allowed the change in the Performance Ratio or the solar generator efficiency per year to be determined.

1 A / B *Two PV power plants that have delivered constant yields since they started operation (from left): 60 kWp on the badenova stadium in Freiburg, and a free-standing 2 MWp system in Bavaria.*



2 *The Performance Ratio of a 2 MWp PV power plant has been constant for six years. The graph shows 5-minute-average values measured at typical irradiance and temperature levels (orange points are after removal of outliers).*

The result for a study carried out in 2010 is that the Performance Ratio of the whole PV system for the investigated systems with monocrystalline or polycrystalline modules has changed by -0.1 % per year on average. The efficiency value of the solar generators had not changed on average. This information indicates that there is no need to make allowance for continuous degradation of monocrystalline or polycrystalline modules when yield predictions are calculated. For a reliable result, it is essential that the irradiance is continuously measured correctly over the analysed period of time. When sensor signals drift, i.e. a given irradiance value does not result in the same sensor signal after a certain period of time, the results are distorted. In order to exclude such an error, all of the sensors were recalibrated for the presented study. Fundamentally, replacement of the sensors every two to three years is recommended for modern monitoring systems.

1

MEGAWATT LABORATORY FOR CENTRAL INVERTERS

Not only the photovoltaic share of the total generated electricity is increasing, but also the dimensions of the PV power plants and the power ratings for the solar inverters. Fraunhofer ISE has reacted to this development by establishing its so-called megawatt laboratory, and is now equipped to operate and measure large inverters with a power rating of up to 1.25 MW. On the one hand, this new power electronics laboratory allows inverters to be measured very accurately (e.g. to determine their efficiency). On the other hand, all tests can be carried out according to the new medium-voltage regulations. These regulations describe how solar inverters must contribute to grid control and how they must react to grid faults.

Bruno Burger, Gregor Dötter, Sönke Rogalla,
Stefan Schönberger, Günther Ebert

With the establishment of its megawatt laboratory, Fraunhofer ISE is equipped with a unique power electronics laboratory which was dimensioned specifically for testing and operating solar inverters with a high power rating. The laboratory is connected directly to the public medium-voltage grid (20 kV) via three medium-voltage transformers (each 1.25 MVA). As is usual in large solar parks, the inverter feeds directly via a medium-voltage transformer into the medium-voltage grid. Depending on the choice of transformer and the selected transformation ratios, the AC voltage can be adapted between 255 V and 760 V. The currents of up to 2500 A are conducted into the laboratory via conductor rails (fig. 3).

A separate source transformer feeds a solar generator simulator, which provides the input for the inverter to be tested. An operating power of up to 1.25 MW can be maintained in this way by cyclic operation at the medium-voltage level. Only the losses caused by the equipment and transformers must be compensated by power from the public grid. The cyclic operation at the medium-voltage level is advantageous as it minimises the effect of the solar generator simulator on the inverter and vice versa. The temperature in the laboratory is controlled by a powerful ventilation system.

1 *View into the new megawatt laboratory at Fraunhofer ISE.*

The solar generator simulator consists of several DC sources connected in parallel, which can imitate the electric performance of a solar generator. DC voltages of up to 1000 V and currents up to 1600 A can be supplied. Thus, an array of solar modules with an area of up to two hectares can be simulated in the laboratory. The simulation of various irradiance profiles, solar generator configurations and standardised test procedures can be flexibly controlled with software developed at Fraunhofer ISE.

Using the solar generator simulator, the maximum power point tracking (MPPT) behaviour can be systematically investigated for inverters up to a power of 1.25 MW. This makes it feasible to measure the overall efficiency value of solar inverters, which is determined not only by the conversion efficiency (electrical efficiency) but also by the tracking efficiency (MPPT efficiency).

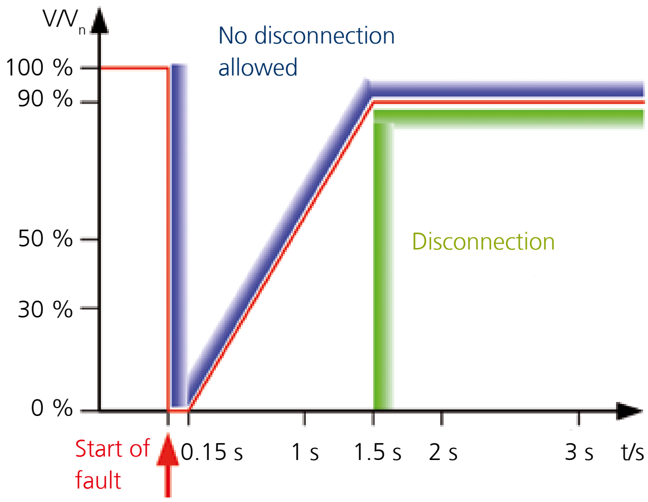
Extremely accurate signal transducers and measurement instruments are available to measure the inverters. These enable accurate measurements of the efficiency value and the quality of the output electricity. Measurements are made at the low-voltage or medium-voltage level, depending on requirements. We developed our own software for the data acquisition and analysis of certain test procedures.

2 *Control desk for the medium-voltage and low-voltage switching circuit and the LVRT test equipment.*

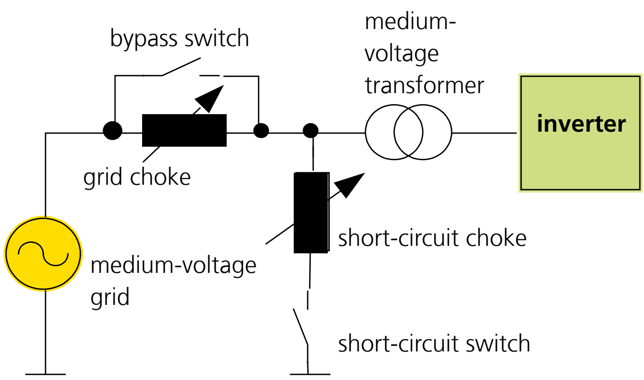
3 *Connection box for inverters with a power rating of up to 1.25 MW.*

The medium-voltage regulation introduced by the BDEW (the German association of energy and water utilities) now demands that also large solar power plants participate in the control and stabilisation of electricity grids, as had been previously demanded only from conventional power stations. In addition to deliberate control of active and reactive power, solar power plants must now also tolerate short-term grid faults and voltage dips (fig. 4). Solar inverter manufacturers must prove that their equipment meets these stringent specifications. This is the only way for the stability of the electricity grids to be guaranteed and the share of regeneratively generated electricity to be increased. The new laboratory offers a unique possibility to inverter manufacturers to comprehensively measure solar inverters over a large power range.

The new megawatt laboratory is equipped with all of the measurement instruments which are needed to carry out the tests demanded by the medium-voltage regulation. Test equipment to investigate the reaction of inverters to grid voltage dips is unique. This so-called low-voltage ride-through (LVRT, see fig. 5) test facility is able to create real voltage dips at the 20 kV medium-voltage level, without disturbing the public supply grid. The voltage dips are created with an inductive voltage divider. Depending on the configuration of the inductive elements, symmetric or asymmetric voltage dips of varying length and depth can be generated. In contrast to mobile equipment housed in a container, which is already operated to test wind power systems, we operate a stationary LVRT test facility which is exactly tailored to the demands of solar inverters. The system can be conveniently operated from a control desk (fig. 2). The gas-insulated medium-voltage switches and the measurement data acquisition system are controlled automatically.



4 *Specifications for solar inverters concerning their continuing grid connection during short-term grid voltage dips. The inverter may not be disconnected from the grid for dips corresponding to conditions above the blue limit line.*



5 *Schematic circuit diagram of the LVRT test facility: The grid choke minimises the effects of the voltage dip on the medium-voltage grid. The ratio of the inductances determines the depth of the dip.*

1

2

BATTERY SYSTEMS FOR AUTOMOBILE AND STATIONARY APPLICATIONS

Electrochemical storage units will play a key role in future for automobile and stationary applications to make a sustainable energy supply and environmentally friendly mobility feasible. We are working in various projects on innovative solutions to offer long lifetimes, high efficiency, great reliability and simple integration into energy systems.

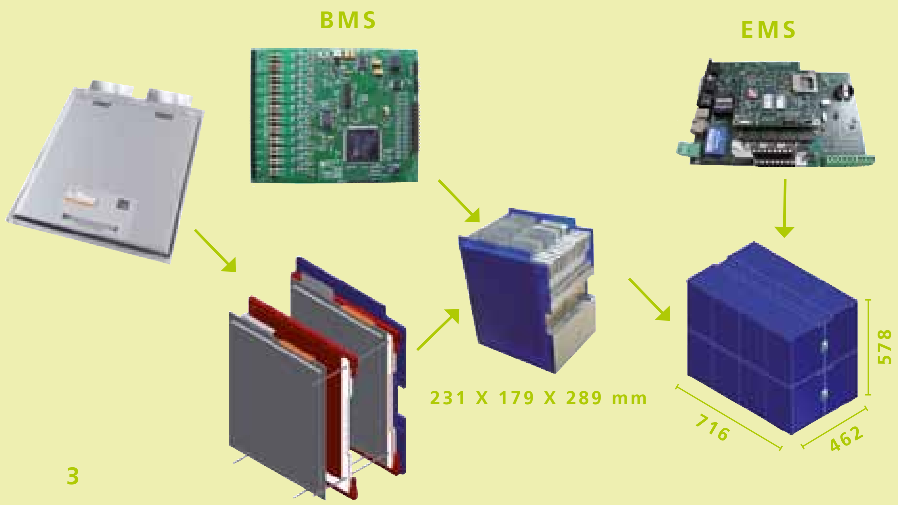
Nils Armbruster, Martin Dennenmoser, Stefan Gschwander, Max Jung, Stephan Lux, **Simon Schwunk, Matthias Vetter,** Günther Ebert

In the automobile sector, the industry is confronting major challenges posed by politics and society against the background of global climatic change. In order to meet the demands for CO_2-free mobility, major efforts are currently being made concerning battery-operated vehicles. The situation is similar for power supply. Up to now, electric storage units in combination with photovoltaics were usually installed only in stand-alone systems. However, the rapid expansion of electricity generators from renewable sources is causing not only grid expansion but also a rapidly increasing demand for stationary electric storage. This is emphasised and supported by the regulation in the German Renewable Energy Law concerning the tariff for on-site consumption of electricity.

The selection of a suitable electrochemical cell for the application in question is a decisive step. Different applications require differing solutions. For example, the energy density is one of the most important criteria for electric vehicles, whereas in the stationary sector, primarily the lifetime in the specific application is decisive. Thus, it is possible that lithium ion cells may be used in both applications, but that they differ greatly in such fundamental properties as the cell voltage due to the choice of electrode material.

In addition to the specifications in data sheets, laboratory measurements are essential to enable selection of the appropriate cell for a given application. This is the only way to ensure uniform quality of the cells. In addition, some properties such as the ability to cycle in the low state-of-charge range can only be determined experimentally. Beginning with the cell, a suitable module consisting of up to twelve series-connected cells is developed, which includes a cooling concept adapted to the relevant demands of the target application. Thus, usually liquid-cooled systems are applied in automobile systems, as the high loads during acceleration and recuperation cause strong cell heating due to resistive losses. In stationary applications, where the specifications on space and power are usually less restrictive, usually cooling based on air ventilation is adequate, instead of the more complicated liquid-based cooling systems. Initially, we simulate cooling concepts with our simulation tools and then test prototypes in the laboratory.

Battery management at the module level already applies intelligent control, which goes beyond the usual tasks of acquiring measurement data on cell voltages and temperatures or cell equalisation to recognise errors and determine the state of charge and state of health at the cell level. Such detailed monitoring of several hundred cells is not possible by the central energy management system for the battery system due to a lack of resources. However, it is necessary for two reasons: Firstly, accurate information on the state of the battery is needed to control it optimally and efficiently. Efficient equalisation, particularly in older batteries, is hardly possible via the voltage alone. Secondly, not much experience has been gained yet with these batteries in real, long-term applications. Monitoring the internal conditions such the state of charge and state of health allows the operating battery systems to be rapidly analysed without the need for complicated and expensive laboratory tests.



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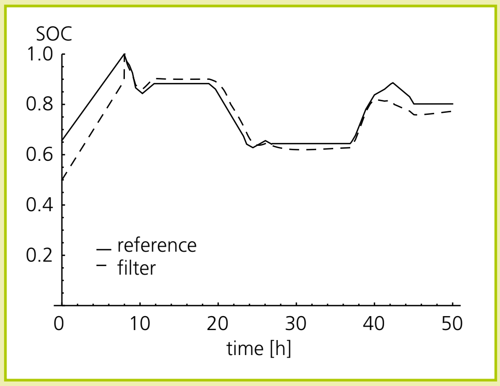

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With our methods, we are also able to determine the state of charge reliably for cells with very flat voltage characteristic curves, e.g. for $LiFePO_4$ / graphite, and to offer exact solutions. These algorithms run on our embedded systems with small processors and low energy consumption. An essential pre-condition for this, apart from understanding of the controls technology and electronics, is profound background knowledge of the different possibilities and characteristics of the individual types of battery technology.

To validate the algorithms for state of charge and state of health, real batteries in different states of health are subjected in our laboratories to temperature and load profiles corresponding to real operation, and the algorithms are compared with measured data. In this way, reliability can be ensured before the operation starts in the field.

The individual modules are connected to each other and the energy management system via a CAN bus, which has proven its robustness in automobile applications and is also widespread in other sectors.

The hardware and software for energy management is also developed by Fraunhofer ISE. It forms the interface between the battery system and the outer world, and performs e.g. the following tasks in automobile applications:
- monitoring the individual battery management modules
- data storage, logging and error detection
- power prediction for acceleration and recuperation by the electric engines
- determination of setpoints for the internal/external charging devices
- model-based control of the cooling circuit
- cruising range
- identification of modules or packs needing replacement
- safety

1 *Battery module for automobile applications consisting of twelve lithium ion cells.*
2 *Electronics for the energy management system of a battery pack.*
3 *The route from the cell through the battery module with integrated electronics to the battery system with intelligent controls.*
4 *Determining the state of charge for a $LiFePO_4$ battery.*

In developing the algorithms, we apply model-based procedures to test for correct functionality, before we connect a real battery system to the controls hardware. Apart from shorter development periods and higher reliability, a major reason is safety aspects, as lithium ion batteries with their high energy density are a veritable source of danger. The battery systems are taken into operation and tested in our 250 kW test rig. Real usage conditions e.g. in a vehicle can be emulated with a CAN interface and a climatic chamber, and the interaction with the vehicle controls can be modelled. In this way, the system, thermal conditions and controls can be tested, safety gaps can be bridged and improvements carried out.

Some of this work is carried out as part of the "Fraunhofer Systems Research on Electromobility", which is supported by the German Federal Ministry of Education and Research (BMBF).

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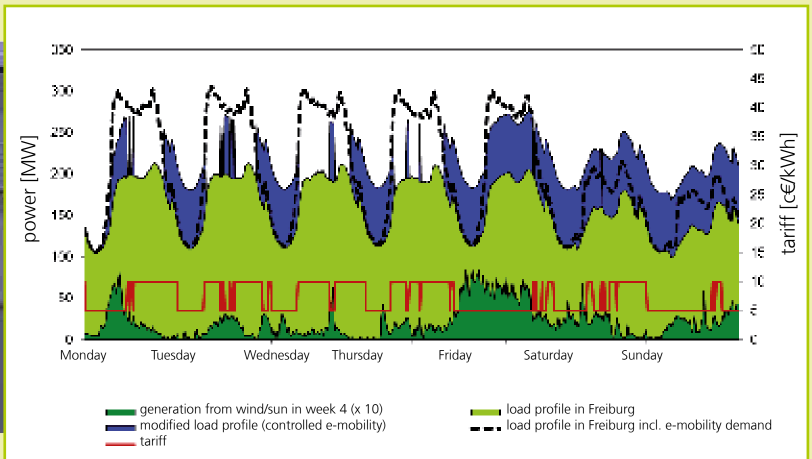

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PERSPECTIVES FOR ELECTROMOBILITY

Renewable energy sources should meet a large share of our energy demand in the coming years. Due to their strong fluctuations, use of storage capacity is inevitable to match demand and supply. Electric vehicles could provide a large proportion of this capacity.

Robert Kohrs, **Bernhard Wille-Haussmann**, Christof Wittwer, Günther Ebert

In the foreseeable future, most of our electricity demand will be met by renewable energy sources or distributed electricity generators. Figure 1 illustrates the vision of a future "Smart Home" with many distributed generators. This transition challenges our current energy system to integrate new loads, storage units and generators. In addition to avoiding local grid shortages, it will be necessary to adopt new approaches to balance consumption and generation. In future, a decreasing number of large, conventional power stations will be available for control functions, so that fluctuating and distributed generators and loads will have to carry out these tasks. Access to new storage capacity will be inevitable for reliable energy management.

Electric vehicles with their batteries could take on a central role in this respect in future. The batteries could be charged when there is a surplus of renewably generated energy, e.g. major production from offshore wind energy systems in the North Sea. Equally, electric vehicles could support the grid by delivering electricity at short notice when the wind is still or during days with little solar radiation.

Nevertheless, this assumes that new methods for connection and accounting are available. To ensure this, Fraunhofer ISE has developed an innovative mobile gateway for communication, accounting and optimisation.

Within the project entitled "Perspectives of Electric Vehicles", Fraunhofer ISE is investigating the integration of electric vehicles in the energy scenario for 2050.

If charging of electric vehicles is permitted in response to the instantaneous demand (recharging after completion of every trip), this additionally raises the midday peaks, which are already high. Figure 2 demonstrates this for the example of a week in Freiburg. The grid peak is raised by about 50 % due to the uncontrolled charging. This results in an additional load on the grid and does not help to integrate fluctuating generators.

It turns out that the CO_2 efficiency of electric vehicles compared to conventional vehicles is greatest when they are operated with electricity from renewable energy sources. As figure 1 shows, uncontrolled charging does not meet this specification. In order to adapt the battery charging to central optimisation criteria, a suitable instrument is time-variable tariffs, which e.g. are communicated and accounted via a mobile metering system. The local optimiser in a vehicle can then decide whether or not to respond to the tariff signal and shift the charging to a low-tariff time.

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

1 *In the "Smart Home" of the future, a large number of electricity generators and shiftable loads such as electric vehicles will be available for energy management.*

2 *An adapted, variable electricity tariff in the Freiburg electricity grid shifts the charging times for electric vehicles into periods with lower loads and a high supply of renewable energy.*

INTELLIGENT CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES

New challenges are arising from the structural transition of our energy supply system to fluctuating, renewable energy sources and the reorientation in the automobile sector toward electric motors, which is just starting. Intelligent charging stations, which enable sustainable integration of electric vehicles into the modern power supply, are essential for this process.

Eduard Enderle, Dennis Freiberger, **Robert Kohrs**, Jochen Link, Michael Mierau, Dominik Noeren, Bernhard Wille-Haussmann, Christof Wittwer, Günther Ebert

Parallel to the adjustment in electricity generation, which demands increasing capacity for energy storage, the mobility sector is also being subjected to major changes. Against this background, electromobility is seen as an opportunity to use distributed storage on a widespread basis. Beyond this, conversion to battery-operated vehicles is environmentally politically acceptable only if the energy for transport is derived from regenerative sources. Thus, several goals are being pursued with an intelligent charging infrastructure: controlled charging, supplying electricity to the grid and rapid charging.

If the vehicle is parked for a time which is longer than that needed to charge the battery, the charging process can be controlled such that charging takes place when supply is greater than demand. Fluctuations in the electricity generated from the wind or the sun can be buffered in this way. The vehicle driver is motivated by variable electricity tariffs to conform to this goal. If the charging infrastructure allows electricity to be fed back from the vehicle battery into the grid, further opportunities are opened up for optimised operation management. Assuming that battery prices fall and that the tolerance of batteries to cycling increases, it can become economically attractive in future to store energy temporarily in vehicle batteries. Participation in the regulatory energy

1 *A charging station developed by Fraunhofer ISE and a Toyota Prius Plug-in Hybrid test car.*

market, or charging the vehicle with electricity which is produced on-site by PV or cogeneration systems and is promoted by the German Energy Generation Law, is also conceivable.

The "Smart Grids" group at Fraunhofer ISE is currently developing and evaluating optimisation algorithms and the hardware for private garages, public charging stations and electric vehicles.

Together with VW and E.ON in the BMU-funded "Electromobility Fleet Test" project and within the "Fraunhofer System Research on Electromobility" funded by the German Federal Ministry of Education and Research (BMBF), we are developing complete charging systems, including AC and DC charging stations and on-board charging optimisers. For an optimised charging strategy, information from the vehicle (battery parameters), the user (trip planning), the grid (dynamic tariffs, grid load, availability of renewably generated electricity) and possibly building energy management is processed. Furthermore, the charging process must be authorised by the energy supplier and data for cost accounting must be transferred reliably. To enable controlled charging already with the first commercially available vehicles, slim systems without communication to the vehicle are being developed within the project on "Efficient Mobility" supported by the badenova Innovationfonds. In addition to the technical systems, it is essential that the vehicles are connected to the grid not only at times when the battery is low. This is primarily a question of user acceptance, which we are also investigating. In parallel, we are evaluating energy-economic concepts to integrate a charging station operator into the liberalised electricity market.

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. For example, a long-term perspective is to store almost unlimited quantities of intermittently generated renewable energy as hydrogen in caverns. 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 80 %. 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 are excellent alternatives or supplements to rechargeable batteries in off-grid power supplies or small electronic appliances, due to the high energy density of hydrogen or alcohol. Even though this application does not immediately represent a large contribution to our total energy supply, it is important in paving the way for the introduction of hydrogen systems.

Research on innovative technology to produce hydrogen and convert it efficiently to electricity and heat in fuel-cell systems forms the core 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 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 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. A technical prototype for gasification of wood is being developed, with which we intend to demonstrate the feasibility of a new process which was developed by Fraunhofer ISE in co-operation with other partners. Furthermore, we are developing a reactor to use energy from biomass consisting of green algae.

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 microscopy or cyclovoltammetry.

The membrane fuel cell, operated with hydrogen or methanol, is our favoured energy converter in the power range from mW to MW, being efficient, environmentally friendly, quiet and requiring little maintenance. In addition to the well-known system configuration based on fuel cell stacks, we have focussed on flat, series-connected miniature fuel cells in a single plane. This design is very suitable for integration into the surface of a casing or as part of a hybrid system in combination with the battery.

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 stand-alone power supplies for off-grid applications and small portable electronic systems.

50-channel impedance spectroscope based on synchronised potentiostat frequency-response analysers (FRA) for spatially resolved characterisation of electrochemical energy converters such as fuel cells, electrolyser cells or redox-flow cells. This equipment allows processes occurring in the cells to be separated by analysing step responses with high temporal resolution and applying electrochemical impedance spectroscopy. Local quantification of the losses occurring on the cell surface is then a guide to deriving the optimisation potential of a cell.

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50-CHANNEL IMPEDANCE SPECTROSCOPY FOR FUEL CELLS AND STACKS

In 2010, two new measurement facilities for extensive characterisation of fuel cells were introduced in the "Fuel Cell Systems" group. These systems are unique in the number of channels and the power range, and support not only traditional polarisation curve measurements but also pulse and current-interrupt measurements with high temporal resolution and electrochemical impedance spectroscopy. Spatially resolved measurements in single cells and single-cell characterisation within fuel cell stacks allow us to identify potential for optimising designs and material selection, and to detect critical operating conditions or localised aging processes.

Robert Alink, **Dietmar Gerteisen**, Ulf Groos, Stefan Keller, Timo Kurz, Walter Mérida, Max Schwager, Christopher Hebling

The strongly coupled complex processes within fuel cells, such as electrochemical reactions, transport of reactants, products, charge carriers and heat, and degradation effects, still pose major challenges to research today. In order to raise the efficiency and improve long-term stability, the processes must be separated and analysed.

Electrochemical impedance spectroscopy represents a powerful characterisation method, which can differentiate between processes with different time constants. Applying this measurement method at different positions within a segmented fuel cell allows spatially resolved analysis at the cell level. In this way, inhomogeneity in the humidity, temperature or gas concentration over the active surface can be detected. The investigation of starting and stopping processes is particularly interesting here.

1 *50-channel characterisation system for spatially resolved measurement of current, voltage and impedance spectra.*

A 50-channel characterisation system, consisting of 50 potentiostats and frequency response analysers (FRA), is available to us for spatially resolved impedance spectroscopy and measurements of the current and voltage distribution. Each channel can load the cell segments with up to ± 5 A at a maximum voltage of 3 V per channel, which corresponds to a cell current of up to 250 A. The impedance measurement can be made in a frequency range from 10^{-3} to 2×10^{4} Hz. Special, low-inductance load-connection cables are used to eliminate artefacts due to the system cabling to the cell. As 4-quadrant potentiostats covering a large power range are used, the multi-channel characterisation system can also be used for other energy conversion systems than fuel cells, e.g. batteries or redox-flow cells.

When fuel cells are applied to supply electricity, these are usually electrically connected in series to form a stack. With a highly dynamic, controllable load coupled to a 50-channel FRA, we are able to analyse different operating states of the single cells in the stack by simultaneous impedance spectroscopy. During the experiments, the ambient conditions can be determined and maintained by an 8 m^3 climatic chamber with a power of 45 kW. Flooding of channels and pores, and drying of the polymer-electrolyte membrane can be detected. With this system, stacks can be investigated with a total voltage of up to 50 V and 100 A load current.

Information from these analyses can be used to define optimal operating windows with regard to power stability and lifetime for the investigated stacks.

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TESTING AND CERTIFICATION LABORATORY FOR FUEL CELL SYSTEMS

The Energy Technology Department at Fraunhofer ISE is currently establishing a testing and certification laboratory to test fuel cell stacks according to standards and to determine the performance data of micro fuel cell systems. The VDE Prüf- und Zertifizierungsinstitut is our partner in this project.

1 *5 kW_{el} fuel cell test facility.*
2 *Climatic chamber for micro fuel cell system.*
3 *Climatic chambers to test fuel cell stacks and systems with power up to 5 kW_{el} (10 kW_{th}).*

Ulf Groos, **Jürgen Wolf**, Christopher Hebling

Standards have already been defined and draft standards are still being prepared for the dimensioning and construction of fuel cell stacks, micro fuel cell systems and portable fuel cell systems. As even the draft standards represent procedures that have been accepted internationally and have been publicly discussed in recognised bodies, they already count as the state of the art. In case of doubt, a manufacturer must therefore prove that products comply with the state of the art analogously to the relevant (draft) standards.

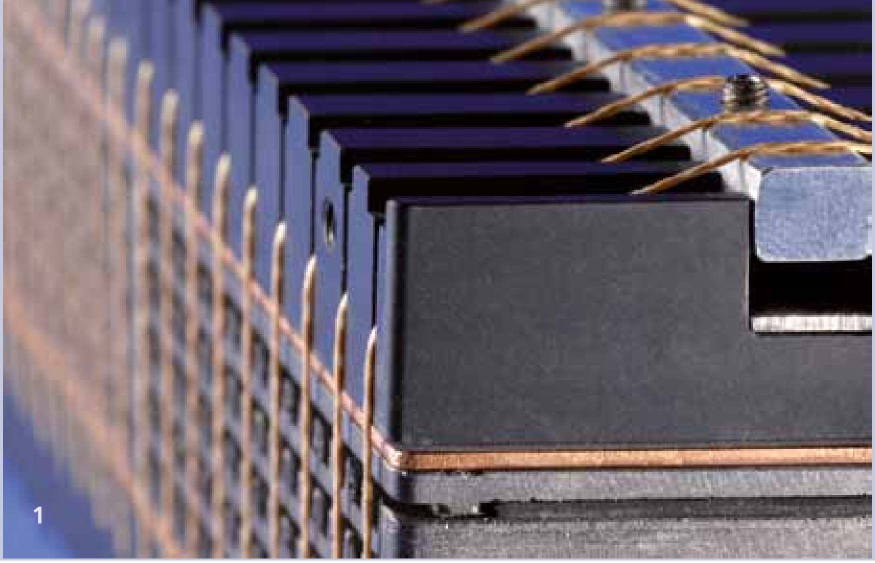
The goal of the project partners, VDE Institute and Fraunhofer ISE, is to establish a testing laboratory to carry out safety tests of small fuel cell systems. The following standards and draft standards are covered: terminology (DIN IEC/TS 62282-1), fuel cell modules (DIN EN 62282-2), portable fuel cell power systems – safety (DIN IEC 62282-5-1), micro fuel cell power systems – safety (DIN IEC 62282-6-1), micro fuel cell power systems – performance test methods (DIN IEC 62282-6-2), micro fuel cell power systems – fuel cartridge interchangeability (DIN IEC 62282-6-3).

The VDE testing institute and Fraunhofer ISE offer advice on development in compliance with standards, failure mode and effects analysis (FMEA), tests according to standards and certification. Two test facilities for up to 1 kW and 5 kW, a low-pressure chamber and a walk-in climatic chamber are being installed. The climatic chamber can be supplied at a rate of up to 2000 m^3/h with fresh air, which can be conditioned to temperatures between -20 °C and +60 °C to maintain operating temperatures between +5 °C and +60 °C in a relative humidity range from 10 % to 95 %.

The following tests according to standards are carried out at Fraunhofer ISE:

Fuel cell modules up to 5 kW
Gas leakage test, normal operation, allowable operating pressure test, pressure resistance test of cooling system, electrical overload test, overpressure test, dielectric strength test, differential pressure test, flammable gas concentration test, test of anomalous conditions.

Micro fuel cell systems
Starting duration, rated power test and rated voltage test, power generation test after disuse, power generation test at high and low temperatures, test under high and low humidity conditions, altitude test, test of fuel consumption, drop test Beyond this, all tests on fuel cells and fuel cell systems can be carried out for which the test facilities and the climatic chambers are technically suitable, e.g. characterisation of single cells and modules, climatic tests, impedance measurements and many more. At present, the test rooms have been prepared, the equipment has been ordered and some of it has been delivered. The laboratory should start operation in the first half of 2011. The project is supported by the "National Innovation Programme for Hydrogen and Fuel Cell Technology" (NIP).



HIGH-TEMPERATURE MEMBRANE FUEL CELL FOR PORTABLE APPLICATIONS

We have developed a fuel cell module using a new membrane technology, to supply electricity to portable devices. This high-temperature polymer electrolyte membrane (HTPEM) can be operated at temperatures above 100 °C and thus features different operating behaviour to previous low-temperature membranes. With the help of innovative materials and a novel system design, we have succeeded in using the properties of this type of membrane to develop a compact, portable fuel cell module with stable operating performance.

Ulf Groos, Julian Keller, **Timo Kurz**, Christopher Hebling

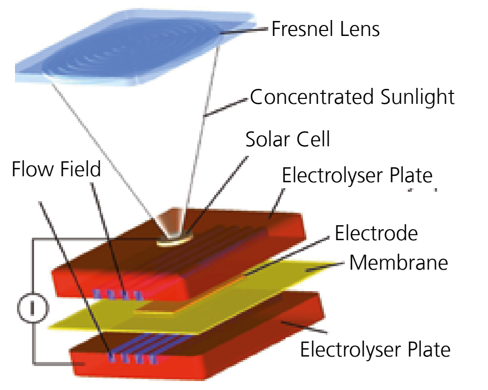
Polymer-electrolyte membrane (PEM) fuel cells offer an efficient alternative to rechargeable batteries or combustion motors to supply electricity to portable devices. However, to date they have still required pure hydrogen as the fuel, which is complicated to generate and store. In addition, conventional PEM fuel cells rely on humidification of the cell membrane during operation. A membrane type made of polybenzimidazole (PBI), which has been available only for a few years, promises to solve both problems. Higher cell temperatures of up to 200 °C become possible when this membrane is used. The fuel cell is then able to use reformate gas from liquid fuels. In addition, the cell membrane no longer needs to be humidified.

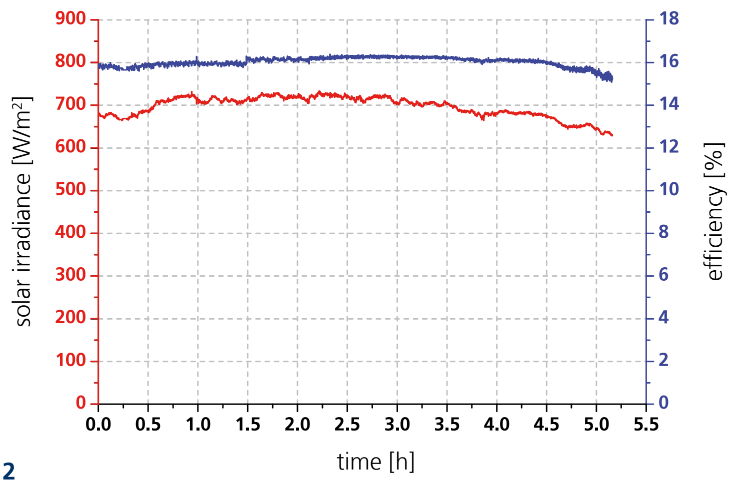
Nevertheless this membrane imposes new demands on the operating conditions due to its increased degradation at high voltages and greater sensitivity to liquid water at low temperatures. We have developed a module which provides optimal operating conditions for this type of membrane and yet has a compact and simple configuration. By applying polymers which are resistant to high temperatures and a novel pressing concept with a wound cord, both mass and volume can be saved in comparison to pressing with threaded rods. As the PBI membrane no longer depends on being humidified during operation, the cell can be operated with a comparatively high air flow rate. With the help of numerical fluid dynamic simulations, flow channels were designed which transport both the cooling air and the air needed for the reaction, and simultaneously ensure an even temperature distribution and a low pressure drop within the cell stack. This design allows a single ventilator with a low power consumption to be used, which minimises the peripheral losses of the system in comparison to other cooling concepts.

In order to test the functionality of the structural solutions, a module prototype with a rated power of 45 W_{el} was comprehensively characterised. The thermal characterisation resulted in an achievable initial heating time of less than 10 minutes. The cell stack displays a maximum temperature difference of 9 °C under normal operating conditions. The applied cooling concept enables dynamic cell performance and the system can be easily modulated between 5 and more than 90 W_{el}. Characterisation with electrochemical impedance spectroscopy reveals a very low impedance of all cells over a wide temperature range and sufficient gas transport through the channels. The module can be upscaled and can thus be used in a power range up to app. 500 W_{el} for portable applications such as robotics, low-power traction or measurement technology. Due to its high tolerance to foreign gases, it is also suited for combination with reforming systems and thus for use with common liquid and gaseous fuels.

1 *Detail of the fuel cell stack: upper pressing plate with the wound cord and a tensioning rail to apply the pressing force.*

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





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H_2 GENERATION BY ELECTROLYSIS WITH RENEWABLE ENERGY

Hydrogen is regarded as a very promising form of secondary energy. In addition to industrial-scale production by reforming, it can also be generated by CO_2-neutral electrolysis of water if electricity from renewable energy resources is used. Applying a patented procedure, we have succeeded in reaching an efficiency value of more than 16 % for converting sunlight into hydrogen.

Frank Dimroth, Gerhard Peharz, **Sebastian Rau**,
Tom Smolinka, Aurelien Yanwouo, Christopher Hebling

CO_2-neutral hydrogen can already be produced efficiently today by suitably connecting a PEM electrolyser (polymer-electrolyte membrane) with regeneratively generated electricity from solar cells. In conventional systems to produce solar hydrogen, PV modules are connected directly to a central electrolysing unit via a DC/DC converter. The disadvantages of this approach are the relatively complex system configuration and the high investment costs. This technology could thus not become established due to the resulting high hydrogen generation costs.

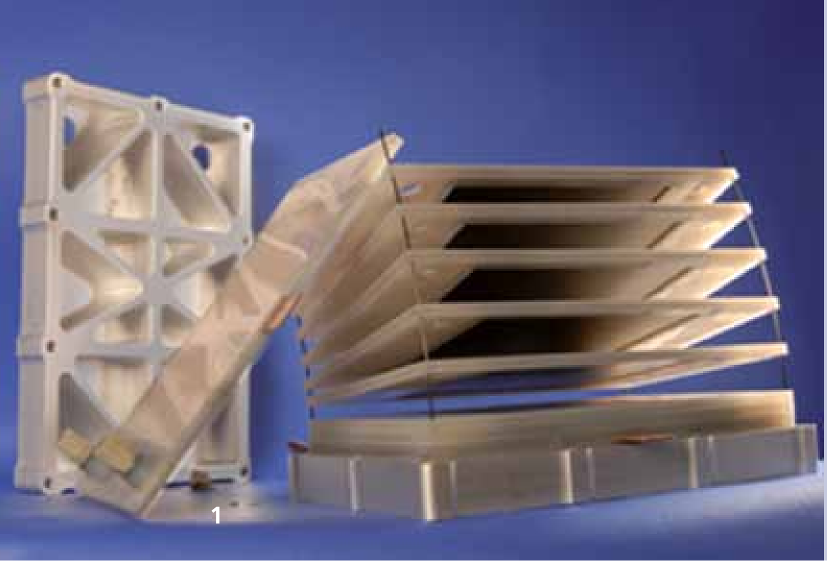
A process which has been patented by Fraunhofer ISE allows the PEM electrolysis cell to be integrated directly into a solar concentrator module (fig. 1). In this way, fewer individual components are needed. In addition, the losses which result from connecting solar cells within the module are reduced. In effect, each solar cell generates its own hydrogen, which is then removed as a gas bubble. The efficiency is particularly high, as only low-density currents flow. This concept is known under the name of "Hydrogen Concentrator" (HyCon®).

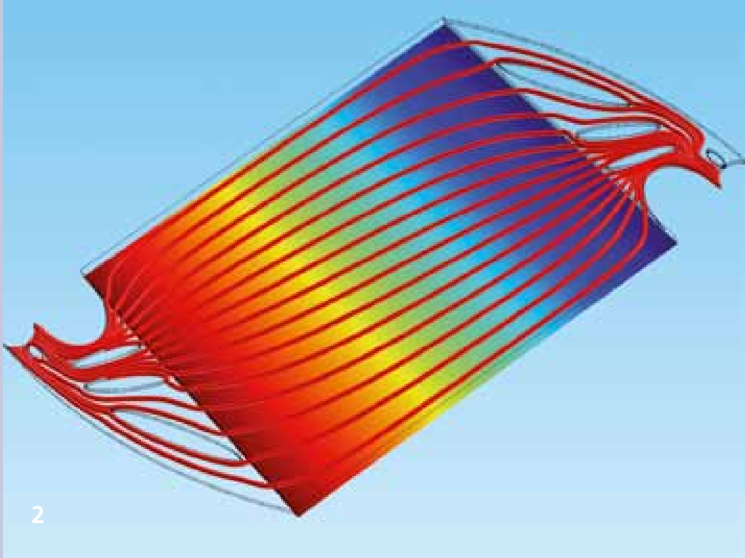
1 *Direct connection of a concentrating solar cell with a PEM electrolysis cell.*

2 *Highly efficient conversion of solar energy into hydrogen. Results measured for a HyCon® cell during an outdoor test in Freiburg, October 2010.*

In this process, only sunlight and water are required for the hydrogen production. At the same time, oxygen is produced in the PEM electrolysis cell, which can also be used. Field measurements in Freiburg have reproducibly demonstrated that efficiency values of more than 16 % can be achieved for converting sunlight to hydrogen with the HyCon® concept, for a direct radiation intensity of app. 700 Wm^{-2} (fig. 2). In order to increase the efficiency further, current research activity is concentrating primarily on optimising the PEM electrolysis cell. At present we are investigating an improved cell design, in which the water supply to the cell interior is as homogeneous as possible and electrochemical overvoltages are reduced. In addition, we are surveying alternative materials which could be used in such a HyCon® cell. As expensive titanium is a main constituent of modern electrolysis cells, its use should be minimised as far as possible or the material should be completely substituted. The resulting cost reduction should allow regeneratively generated hydrogen to be produced at competitive prices in future. The highest possible hydrogen yield can be achieved with this concept primarily in countries with a high proportion of direct radiation, e.g. Spain or Northern Africa.

The work is partly supported by the E.ON International Research Initiative.





SIMULATION-SUPPORTED DESIGN OF CELL STACKS FOR REDOX-FLOW BATTERIES

At Fraunhofer ISE, we are addressing the stack and system development and battery management of redox-flow batteries as preparation for developing a scalable electric storage unit for an electric power of 100 kW$_{el}$ and a capacity of 1 MWh$_{el}$. We apply simulation-supported analysis and design of redox-flow batteries to identify optimisation potential at the cell and stack level and implement it in further design development.

1 *Cell stack with an active area of 700 cm², consisting of 18 cells with a rated power of 1 kW.*

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

Kolja Bromberger, Martin Dennenmoser, Peter Gesikiewicz, Beatrice Hacker, Andreas Kaiser, Karsten Koring, Felix Oßwald, Tobias Schwind, Tom Smolinka, Matthias Vetter, Christopher Hebling

Redox-flow batteries store electricity as chemical energy in the active mass of liquid electrolytes, which are stored in 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.

Within the BMU-funded project on "1 MWh redox-flow grid storage units", at Fraunhofer ISE 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 in combination with electricity generators from renewable energy sources. Figure 1 shows a cell stack with an active area of 700 cm², which is characterised by a power of app. 1 kW$_{el}$ for a stack of 18 cells. Cycling efficiency values exceeding 80 % can be achieved at the cell level.

With CFD simulation, fundamental fluid-technological questions are answered concerning the design of the inlet and outlet zones at the cell level, distribution structures, liquid management within the stack and geometrical relationships. Using the 1 kW cell design as an example, fig. 2 shows the flow patterns of the electrolyte through a half-cell and the pressure loss across an electrode material. In parallel, we test and develop suitable sealing concepts for cell stacks of 5 kW and more.

To reduce the storage costs, cell designs are developed 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, such as electrolyte temperatures, pressure losses across the cell stack, flow rates of the electrolyte circulation and single cell voltages, is available for characterisation and evaluation purposes.

Starting from these measurements, we develop model-based control strategies in parallel, which allow energy-optimised operation of the redox-flow battery system. The so-called "smart redox flow control" allows an optimised mode of operation by minimising energy losses in the peripheral devices and well-matched integration (i.a. by state-of-charge prediction) in the higher-order energy system, which lengthens its lifetime. In addition, charging and discharging strategies allow an inverter to be connected.

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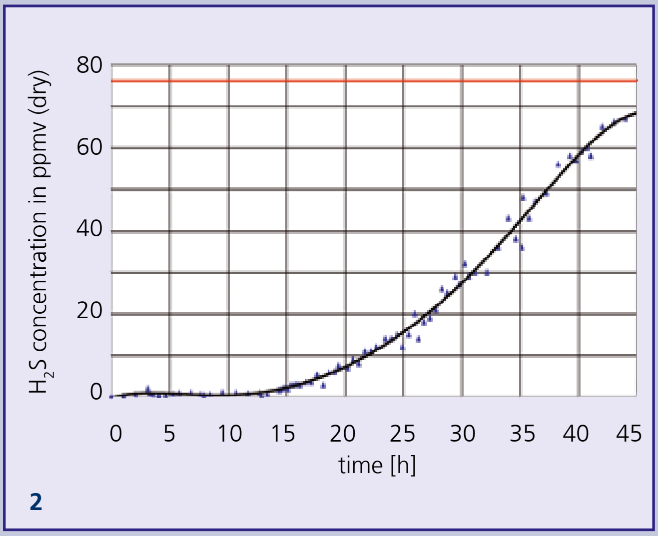

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DESULPHURISATION OF REFORMER PRODUCT GASES WITH ZINC OXIDE

Many fuels contain sulphur compounds, which are mainly converted during reforming into hydrogen sulphide (H_2S). The reformer product gas usually contains only traces of H_2S, but this is sufficient to deactivate subsequent catalysts, e.g. in the fuel cell. For this reason, the H_2S concentration after the reformer should be as low as possible. As part of an industrial project at Fraunhofer ISE, a process was optimised, in which zinc oxide is used for desulphurisation. A high sulphur loading of approx. 15 wt. % was proven experimentally. The H_2S concentration at the exit of the zinc oxide filter exceeded the critical limit of 1 ppm (parts per million) only after this sulphur loading had been reached.

Thomas Aicher, **Achim Schaadt**, Florian Zernikau, Konstantinos Zonaras, Christopher Hebling

Reformers convert commercially available fuels into hydrogen and thus allow existing and cost-effective infrastructure to be used. In combination with fuel cells, high electrical efficiency values can also be achieved in partial-load operation, while the emission of flue gas and noise is simultaneously reduced. The sulphur concentration in fuels has become appreciably lower in recent years due to legal requirements. Nevertheless, it is still so high that the catalysts following the reformer in reformer/fuel cell systems are irreversibly damaged.

The reformer catalyst itself tolerates the sulphur concentration found in conventional, commercial diesel fuel without significant losses in reactivity. The reformer can thus be operated with common diesel fuel. The chemical reactions in the reforming process release the sulphur that is poisonous for catalysts in the form of hydrogen sulphide. In the process which we investigated, hydrogen sulphide at a temperature of 300–350 °C passes through a bed of zinc oxide pellets (ActiSorbS S2 from Süd-Chemie AG), which bind it chemically. The challenge was now to carry out the reaction according to our industrial client's specifications in the smallest possible reactor volume and in a way which ensured that the output concentration did not exceed approx. 1 ppm. To do this, it was necessary to set up sulphur analyses which can detect such low concentrations reliably. In addition, the zinc oxide bed was required to adsorb as much H_2S as possible, as this would reduce the number of maintenance pauses to change the zinc oxide cartridge in the later system. Figure 1 shows the result of an experiment in which a synthetic reformer product gas with an initial concentration of 76 ppm H_2S (relative to the dry gas) was introduced into the zinc oxide bed. In order to determine when the H_2S concentration increased at the bed exit in the shortest possible time, only a very small volume of pellets (1 cm^3) was used. At the same time, the gas flowed through the zinc oxide bed with a relatively high flow rate (2.5 N l/min). The gas hourly space velocity was 150 000 h^{-1}, so that gas flowed through the pellet bed volume 150 000 times an hour under standard conditions. It was determined that a pellet-bed volume of only one cubic centimetre was sufficient to lower the H_2S concentration from 76 ppm to approx. 1 ppm for about 14 hours. This was only possible because the sulphur loading reached the high value of 15 wt %.

1 *Zinc oxide pellets (ActiSorbS S2 from Süd-Chemie AG).*

2 *Breakthrough graph for a gas mixture flowing through the ZnO bed (76 ppm H_2S).*

REGENERATION OF SOOT PARTICLE FILTERS WITH FUEL VAPOUR AND SYNTHESIS GAS

The soot particles emitted primarily by diesel motors and direct-injection petrol motors can be inhaled into the lungs and can cause cancer. They must therefore be removed from the exhaust gas by suitable filter systems. The particle filter becomes loaded with soot and must be regenerated from time to time. A certain exhaust gas or filter temperature is needed to regenerate the particle filter. A fuel evaporator that had been developed at Fraunhofer ISE was installed and successfully tested in the motor test stand at MAN Nutzfahrzeuge AG. The evaporated fuel could already be ignited at low exhaust gas temperatures at the following oxidation catalyst. This means that the filter can be regenerated also at operating points corresponding to light loads.

Thomas Aicher, Stefan Riederer, Malte Schlüter,
Robert Szolak, Christopher Hebling

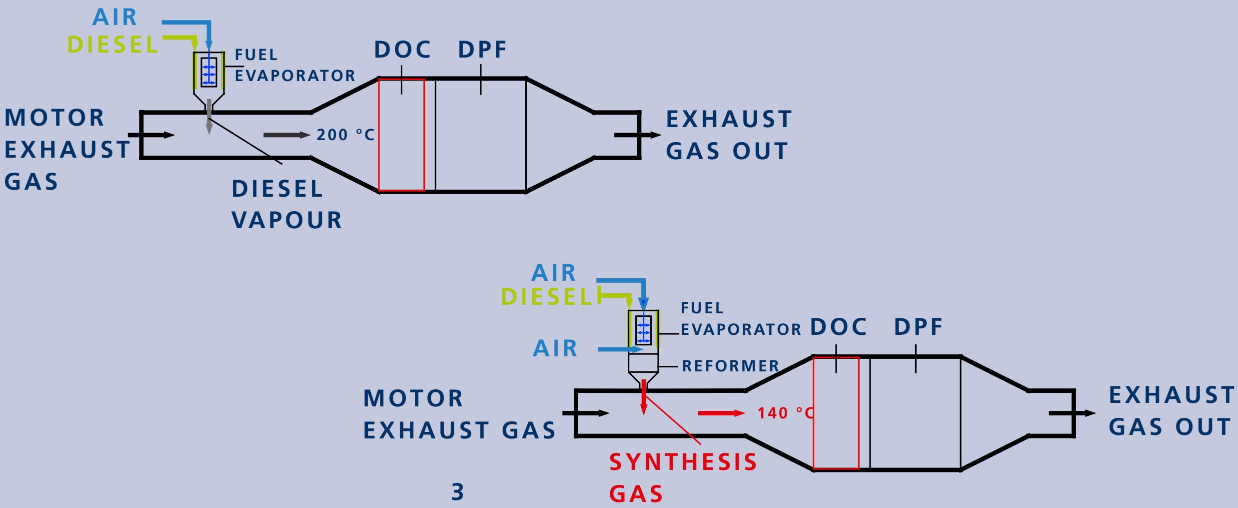
With the introduction of the Euro 5 standard in 2009, the limits for particle and nitrogen oxide emissions were lowered appreciably. These limits cannot be met by motor-based measures alone. Additional measures are needed such as the installation of particle filters.

Particle filters are loaded with soot until a maximal allowable opposing pressure from the exhaust gas is reached. Then the filters are regenerated by burning off the soot. Usually, a filter temperature of more than 600 °C is required for this process, but this regeneration temperature is not reached in motor operation. A common process to regenerate the distributed particle filter (DPF) is a combination of the continuous regeneration trap (CRT) process and fuel post-injection. In the CRT process, the nitrogen monoxide that is contained in exhaust gas is converted to nitrogen dioxide in a diesel oxidation catalyst (DOC). The nitrogen dioxide can oxidise the soot at significantly lower temperatures than the molecular oxygen in the exhaust gas. The filter can thus be regenerated already at about 270 °C. Depending on the operating state, however, either the required amount of nitrogen dioxide or the necessary temperature cannot be provided. For this reason, liquid fuel is injected if the soot loading of the filter is too great. The fuel is oxidised in the DOC by residual oxygen in the exhaust gas. The resulting increase in the exhaust gas temperature heats up the DPF and oxidation of the deposited soot starts by nitrogen dioxide and residual oxygen in the exhaust gas.

1 *Truck motor, MAN Nutzfahrzeuge AG.*
2 *Fuel evaporator, Fraunhofer ISE.*

However, DPF's could not be effectively regenerated at all operating points for a vehicle. In particularly, in light-load operation (e.g. city driving), the exhaust gas temperature is often too low to oxidise the injected fuel completely at the DOC. In the direct injection of liquid diesel, the fuel is evaporated in the flowing exhaust gas. Due to the enthalpy of evaporation, heat is extracted from the exhaust gas and its temperature falls. Thus, if the exhaust gas temperature is too low, condensation can occur in the DOC, the condensed fuel can occupy the catalyst surface and even damage it. This can be prevented by pre-evaporation of the diesel. Condensation effects can be avoided in this way and additionally, the DPF can be regenerated at a low exhaust gas temperature.

Fraunhofer ISE has developed a new process to evaporate the diesel fuel. Some fuels, such as diesel, heating oil and bio-oils, form residues during conventional evaporation methods. With



3 *Procedure to regenerate soot particle filters. The pre-evaporated fuel is added to the exhaust gas string. The soot particle filter can still be regenerated at exhaust gas temperatures down to 200 °C (above). A reforming unit has been added to the fuel evaporator. It produces a synthesis gas, which can be ignited together with the exhaust gas from the motor at 140 °C. The soot particle filter can thus be regenerated at all operating points (below).*

this new process, it is possible to evaporate diesel, heating oil and bio-oils without creating residues. The fuel evaporator is simply constructed and very robust. A small amount of the fuel is oxidised at a catalyst and the heat generated thereby is used for complete evaporation of the fuel. The additional amount of air is substoichiometric (air coefficient of app. 0.1). The heat is transferred primarily by radiation from the catalyst to the surface of the fuel film. The reactor wall, where the fuel is introduced, is always colder than the fuel itself, so no deposits or crusts are formed. The fuel evaporator must be heated up only at the beginning of the process. After the start, the external heater can be switched off. For the start, it is sufficient to heat the catalyst. Due to the small thermal mass, very short heating times can be achieved. The fuel evaporator is thus very well suited for mobile applications.

The fuel evaporator that was developed at Fraunhofer ISE was installed and successfully tested in the motor test stand at MAN Nutzfahrzeuge AG. A diesel motor (type D 2066) with 286 kW was used. The experiments were carried out with the fuel evaporator and the HCI system (hydrocarbon injector) with air-assisted fuel injection. They demonstrated that the soot particle filter can be regenerated at lower temperatures by the fuel evaporator. The fuel evaporator displayed good dynamics during the experiments; the soot particle filter could also be regenerated in the bus cycling mode.

Due to modern combustion processes, the temperature of exhaust gas from diesel motors is increasingly lower. In addition, more motors are being offered with automatic start-stop operation. The exhaust gas temperature can then be clearly lower than 200 °C (app. 160 °C). The HCI system can no longer be applied without additional features at these exhaust gas temperatures. At Fraunhofer ISE, we have thus carried out investigations to demonstrate the influence of synthesis gas on the ignition temperature of the DOC. For the investigations, the exhaust gas composition was adjusted to correspond to light-load operation. Synthesis gas instead of the evaporated diesel fuel was added to the exhaust gas. The ignition temperature was reduced to 140 °C in this way. Thus, with synthesis gas, the particle filter can be regenerated in all operating modes, even with modern combustion processes. To generate the synthesis gas, only a reforming reactor must be added to the fuel evaporator. The fuel vapour reacts in the reformer with additional air to form synthesis gas. The amount of additional air is also strongly substoichiometric (air coefficient of app. 0.3). The fuel evaporator and the reforming reactor are mounted within a single housing. Very short start times can be achieved with this compact configuration. No external heating is needed after the start. Due to the fuel evaporator, it is possible to mix the additional air for the reforming homogeneously with the fuel vapour. Soot deposition in the reforming zone is avoided in this way.

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 units: TestLab Solar Thermal Systems, TestLab Solar Façades, TestLab PV Modules and the calibration laboratory with CalLab PV Cells and CalLab PV Modules. Our further service units include an inverter laboratory, a test facility for compact heating and ventilation units, a laboratory for quality control of phase change materials (PCM), a test stand for thermally driven heat pumps, a battery testing laboratory for cells and systems and a lighting laboratory.

Beyond the service aspect, these units also have a research function for us. 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 collector testing
- hail test stand
- system and storage tank test stand
- outdoor test stand with trackers and a dynamic rack
- indoor test stand with a solar simulator
- 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 unique 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. TestLab Solar Thermal Systems was extended considerably also in 2010 and now offers an even wider range of possibilities for co-operation (see article on p. 121).

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, façade components and windows, 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 article on p. 122).

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

TestLab PV Modules was also accredited in 2006, including testing for product type approval of PV modules according to IEC 61215 and 61646. Since 2010, all testing and measurement equipment is located in a single building, so that the testing sequences can be carried out yet more efficiently and faster. 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 carries out the safety tests and 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 calibration laboratory at Fraunhofer ISE, comprising CalLab PV Cells and CalLab PV Modules (see article on p. 118).

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. 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 article on p. 119).

The TestLab PV Modules at Fraunhofer ISE tests and certifies PV modules according to IEC 61215 and IEC 61646. The test equipment includes a climatic chamber for combined exposure to UV radiation and damp heat. In it, PV modules are weathered and tested with UV radiation (max. 250 Wm^{-2}), humidity (max. 60 % relative humidity) and elevated temperatures (max. 90 °C).

At the Battery Laboratory at Fraunhofer ISE, all common technological types and designs of batteries and battery systems are tested and characterised for manufacturers, system integrators and users. Flexibly programmable battery testing instruments for up to 250 kW power are available to apply whichever charging and load profiles are needed. The spectrum ranges from small cells for consumer appliances to large battery packs for stationary and automobile applications. We carry out electrical and thermal characterisation and aging tests.

In the lighting technology laboratory, we test and characterise lamps and lighting systems of all commonly available types and configurations for manufacturers and users. Our laboratory equipment is specifically designed for testing photovoltaically powered lighting systems in the low power range. Beyond this, grid-connected standard lamps and lights can also be measured. Our focus is always on the complete system, i.e. lamps together with electronic controls and peripheral optics, plus the photovoltaic power supply (PV generator, charge controller, DC/DC converter) for off-grid lighting.

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Ventilation units and heat pumps	Thore Oltersdorf Test stand	Phone +49 761 4588-5239 thore.oltersdorf@ise.fraunhofer.de

www.callab.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 (www.callab.de) 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, Luca Greco, Jochen Hohl-Ebinger, Thomas Hultzsch, Katinka Kordelos, Simone Petermann, Michael Schachtner, Holger Seifert, Astrid Semeraro, **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. We have implemented a new procedure, with which temperature coefficients can be determined with a previously unattainable accuracy. The crucial element is measurement of the temperature-dependent spectral response.

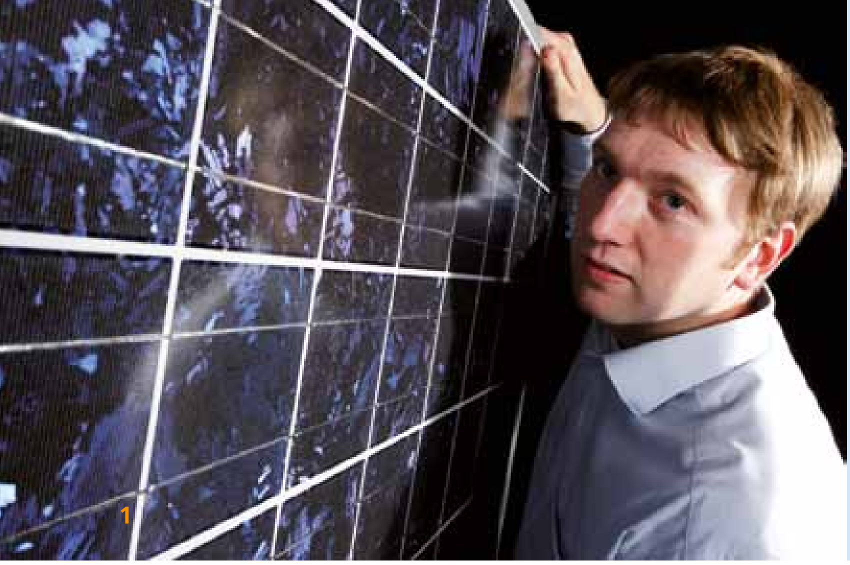
In the middle of the year, we moved into new laboratories and were able to optimise our measurement facilities with regard to the ambient conditions. This, combined with improved infrastructure, means that we can supply the industry even better than previously with references.

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. With the calibration of organic multi-junction cells, we were able to support the rapid development of this technology 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 in a 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 are working on a solar simulator with six independent light sources for calibrated measurement of solar cells with up to six pn junctions.



CALIBRATION OF PV AND CONCENTRATOR MODULES

CalLab PV Modules (www.callab.de) 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, Jürgen Ketterer, Martin Kaiser, Klaus Kiefer, Ulli Kräling, **Frank Neuberger**, Gerhard Peharz, 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.

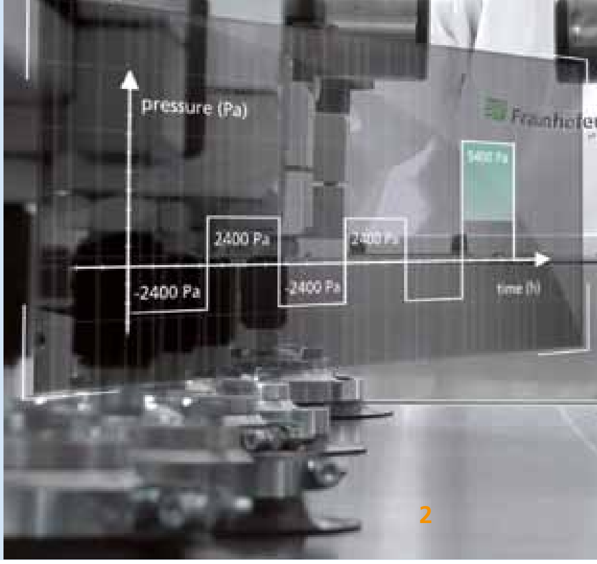
In addition to our solar simulators, we have further equipment available, including light-soaking units, outdoor test stands and spectrometers for complete characterisation of PV modules. Our long experience in the module calibration sector, combined with modern measurement equipment and efficient work processes allow us to carry out complex, client-specific tasks within a short time.

1 *Preparation for power measurement of PV modules at Fraunhofer ISE.*

2 *FLATCON® concentrator module mounted on the tracker unit for measurement of the current-voltage characteristic under outdoor conditions.*

Measurement of concentrator modules

Measurements of concentrator modules are generally made outdoors. To do this, we operate a tracker unit 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.



EXPANDED CAPACITY TO TEST AND CERTIFY PV MODULES

In 2010, the testing capacity of the TestLab PV Modules was further expanded and the testing equipment was concentrated in adjacent rooms. This meant that the testing sequences could be optimised and the time to test PV modules for type approval according to IEC 61215 and 61646 has been reduced further.

Holger Ambrosi, Heinrich Berg, Ilie Cretu, Jürgen Disch, **Claudio Ferrara**, Michael Köhl, Kerstin Körner-Ruf, Amelie Köpple, Georg Mülhöfer, Daniel Philipp

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).*

New testing facilities, both those developed at Fraunhofer ISE and those acquired commercially, make faster IEC-based tests and tests according to clients' specifications for R&D projects feasible and allow support to accompany development.

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).

Light-soaking of thin-film modules is carried out in a climatic chamber with a continuous solar simulator (class BBB) at a controlled, constant module temperature. A wide range of parameter studies can be conducted here for new thin-film technology. For example, the modules can be exposed to a certain irradiance level at different module temperatures, in order to determine optimum conditions for stabilising photovoltaic modules based on thin-film technology. During the stabilisation phase, the output power, the radiation intensity and the module temperature are monitored continuously and the characteristic IV curves are measured several times per hour.

Within our cooperation with the VDE Institute, our partner tests electrical safety according to IEC 61730 and issues the type approval certificate after successful completion of all relevant tests. In addition to tests conforming to IEC standards, we also carry out individual tests and test sequences for R&D projects and according to client specifications.

www.testlab-pv-modules.com

1 A

1 B

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, Andreas Jung, **Korbinian Kramer**, Stefan Mehnert, Rahel Ott, Jens Richter, Arim Schäfer, Wolfgang Striewe, Christoph Thoma, Werner Platzer

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.

After extending our test facilities and successfully taking them into operation, we were able to begin new testing activities in TestLab Solar Thermal Systems in 2010. Reacting to the market development, we focussed on the combination of solar thermal systems and heat pumps and established a first prototype measurement.

Another important topic in 2010 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 implemented for the first time. A methodology to characterise many variants of this technology is thus now available at TestLab Solar Thermal Systems.

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

Long and intensive work on our solar air-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.

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 in 2010 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 2010, 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 set standards and define processes.

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**, Werner Platzer, 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 resistance 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

With its professional services, Fraunhofer ISE has made an important contribution to quality assurance of photovoltaic power plants since 1990. Comprehensive quality assurance is needed to ensure that the predicted yield for a photovoltaic power plant is obtained throughout its entire lifetime. Fraunhofer ISE offers a wide spectrum of measures to guarantee this.

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

Yield prediction

An independent yield prediction is an essential first step along the path to optimal yields. Our yield prediction includes two essential criteria to assess a PV plant: the specific yield for the site in question and the Performance Ratio to evaluate the applied technology. By applying our background knowledge and experience from characterising components in our measurement laboratories, we are able to judge and evaluate the specifications appropriately. We regularly compare our predictions with measured results from our long-term monitoring services.

Module measurements

Over an operating period of 20 years, one percent less module power in a megawatt plant already means a loss of around 100,000 euros. We thus offer a statistically representative power measurement of solar modules in our calibration laboratory to investors and operators, so that possible deviations can already be detected before installation of the system. To select the modules from the manufacturer's "flash list", we have developed a special procedure which enables reliable assessment of the performance of all modules from a very small fraction of modules (about 1 %).

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

System testing

So that we can be sure that our clients' systems also really correspond to the state of the art and supply the predicted power, we offer extensive complete examination of the entire system. In this way, appropriate corrective measures can be taken in time and possible claims against system suppliers or manufacturers can be filed. The examination includes general identification of faults and determination of deviations from the specifications in the yield prediction. To check the performance of the solar generator, the characteristic curves of sub-generators or individual strings of the solar generator are measured. Safety-relevant tests are carried out by our cooperation partner, the VDE Institute. Our testing procedures and test reports are internationally recognised by investors and banks.

Monitoring of PV system quality

Independent confirmation of the quality and performance of PV products and systems is highly relevant for banks and investors. We offer reliable and accurate PV monitoring solutions to manufacturers and project developers. Our experts prepare qualified error messages and high-quality analyses of the operating ranges of the system components. The result is early recognition of suboptimal operation and thus the restoration of valuable yields. Major project developers have clearly improved the performance of their systems by continuous cooperation with Fraunhofer ISE – as is documented by a comparison of the Performance Ratio for systems monitored by us and for 100 further comparable systems equipped with internal company monitoring.

CHARACTERISATION AND TESTING OF BATTERIES AND BATTERY SYSTEMS

We test and characterise all common technological types and designs of batteries and battery systems for manufacturers, system integrators and users. Flexibly programmable battery-testing equipment is available to apply whichever charging and load profiles are needed. Our spectrum ranges from small cells for consumer appliances to battery systems for automobile applications. We have extensive experience in electrical and thermal characterisation.

1 *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.*

2 *In the power test stand, battery systems with a power of up to 250 kW are tested in a climatic chamber that is filled with inert gas.*

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

Battery Technology

Special lead-acid batteries are mainly used in solar systems and as starter batteries for vehicles. NiCd, NiMH and Li ion cells are used in portable and mobile applications. In hybrid and electric vehicles, mainly so-called zebra batteries or battery systems with complex electronic controls, which are based on lithium-ion or NiMH cells, are applied. Double-layer capacitors are used to supply peak currents of short duration, e.g. to buffer the start-up power for motors. Our battery laboratory is equipped with test units for all of these types of technology. Very complex tests can be carried out either according to the procedures specified by the relevant institutions (DIN, IEC, PVGAP and others), or according to procedures adapted to client specifications.

Test conditions

We test batteries in a water bath or in a climatic chamber, so that the required environmental conditions can be maintained. As a safety precaution, climatic chambers with an inert test environment are available for testing lithium-ion cells and battery systems.

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

In the automobile sector, electrification of the drive unit is currently being promoted vigorously. Battery systems are important components, consisting of NiMH or lithium ion cells, control electronics, cooling systems and protective covers. Our test laboratory is able to measure systems up to a power of 250 kW with currents up to 600 A and voltages up to 1000 V. During testing, the test object can be controlled via a CAN bus and subjected to standardised or freely defined driving cycles. As a safety precaution, the battery system is located during this test in a climatic chamber that is filled with inert gas and is equipped with an additional fire-extinguishing system.

In addition, we offer classic tests for starter batteries such as cold-start tests.

CHARACTERISATION AND TESTING OF LIGHTING SYSTEMS

We test and characterise lamps and lighting systems of all commonly available types and configurations for manufacturers, system integrators and users. Our laboratory equipment is specifically designed for testing photovoltaically powered lighting systems in the low power range. Beyond this, grid-connected standard lamps and lights can also be measured. Our focus is always on the complete system, i.e. lamps together with electronic controls and peripheral optics.

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

2 *PV-powered lamps for characterisation in the lighting laboratory.*

Georg Bopp, Stephan Lux, **Norbert Pfanner**

Lamps

Light-emitting diodes (LED) are being used increasingly today for solar lighting systems. Their long lifetime and excellent efficiency predestine LEDs to be the light source for solar-powered lighting systems. Because the electric power can be simply scaled, completely new lamps can be designed and lamps with very low power can be produced as an inexpensive alternative to petroleum lamps. If more lighting power is needed, e.g. to meet requirements in Solar Home Systems, fluorescent lamps and compact fluorescent lamps continue to be used. Our laboratory is thus equipped to characterise both types of lighting technology.

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 (e.g. over the desk surface), and investigations of the operating performance of the lighting technology under different conditions (e.g. variation of the operating voltage and ambient temperature). We also determine the electrical properties of electronic controls and electronic ballasts, including the efficiency, operating behaviour and fault management.

Long-term tests

Poor-quality LEDs are characterised by rapid degradation of the emitted light, whereas fluorescent lamps react sensitively to switching processes and have shorter lifetimes if the quality of the electronic ballasts is inadequate. Special long-term test stands are available in the lighting laboratory for both types of lamps.

Equipment

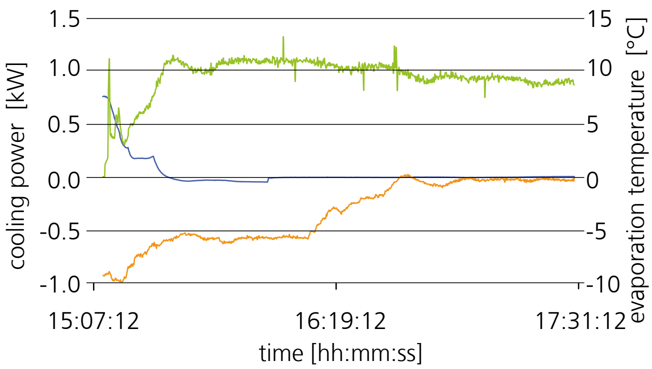
We have the following photometric equipment: software-controlled lighting measurement stand with a photometric sphere of 1.50 m diameter, spectrometers for the visible range, a luminance camera, luxmeters and test stands for determining long-term performance. The following equipment is available for electrical characterisation: Accurate broadband wattmeters, digital oscilloscopes with clamp-on ammeters and galvanically separated probes, and programmable stabilised power supplies.

TEST CAPACITY FOR HEAT PUMPS AND EVAPORATORS

We have now gained practical experience with our new test stand for heat pumps and evaporators. We can cover a wide range of power on the user side – from heating and cooling power of less than 1 kW for reversible heat pumps up to 12 kW heating power. Specific investigations of new evaporators can be carried out with a further test rig, which has recently been taken into operation. We apply the experience we have gained over many years, not only to measure systems in compliance with standards, but also to support manufacturers in new or further development of their products.

Thomas Kramer, Marek Miara, **Thore Oltersdorf**, Jeannette Wapler, Hans-Martin Henning

Since the 1990's, we have been working to improve the heat supply systems for buildings with a very low heating demand (zero-energy and passive buildings, and similar energy-efficient buildings). One focus is the measurement and further development of heat pumps, which use air as the heat source. In broadly based monitoring projects of very different types of heat pump systems, we have considerably extended our competence in evaluating systems that are already installed. On this basis, and by applying powerful design programmes for cooling circuits, we can offer expertise to optimise existing systems or develop new equipment.



2 *Cooling power as a function of time for an evaporator with several heat sources, which can be passively defrosted during operation when the air temperatures are above the freezing point. The graph shows the cooling power for outdoor air (blue) and a simulated solar-thermal circuit (green) as the heat sources, and the evaporation temperature (orange).*

1 *Evaporator with several heat sources.*

We have set up a test stand, in which heat pumps for space heating and domestic hot water can be measured in operation. The measurements are made in accordance with DIN EN 14511 and DIN EN 255-3. Measurements and extensions of the test sequences according to prEN 14825 and prEN 16147 are also possible. The working media of air, water and glycol-water can be combined in our test stand to simulate different heat sources and sinks. The heating power range of the measured heat pumps can be up to 4 kW for air-water systems and up to 12 kW for systems working with sol-water or water-water combinations. Extension of the capacity for air-water systems also up to 12 kW heating power is planned. In component development, we focus on evaporators, for which an additional component test stand was completed in 2010. Particular attention has been devoted to concepts which are designed for the combination of different heat sources. We work here not only with classic fin-and-tube heat exchangers as evaporators, but also with concepts which make the production and stable operation of brazed heat exchangers as evaporators feasible.

Our comprehensive monitoring projects provide measurement results of a quality which closely approaches that of the test stands. This means that the potential for improved control strategies can be exploited and implemented under practically relevant conditions.

APPENDIX

VISITING SCIENTISTS

Nidal Yacoub Abdalla, M.Sc.
National Energy Research Center (NERC)
Amman, Jordan
19.7.–20.8.2010
Research area: Simulation of solar thermal systems

Haitham M. Adas, M.Sc.
National Energy Research Center (NERC)
Amman, Jordan
1.–29.10.2010
Research area: Energy efficiency and solar thermal energy

Matteo Balestrieri
University of Bologna
Bologna, Italy
16.10.2009–30.8.2010
Research area: SPV analysis of silicon surfaces

Mrayyan Dea, M.Sc.
National Energy Research Center (NERC)
Amman, Jordan
1.–29.10.2010
Research area: Energy efficiency and solar thermal energy

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

Andrea Frazzica, Eng.
Consiglio Nazionale delle Ricerche (CNR)
Istituto di Tecnologie Avanzate per l'Energia »Nicola Giordano« (ITAE)
Messina, Italy
1.–30.6.2010
Research area: Thermally driven heat pumps (TAS)

Natheer Halawani, M.Sc.
Lebanese University
Tripoli, Lebanon
2.–6.8.2010
Research area: Simulation of solar thermal systems

Dr Walter Mérida
Associate Professor
University of British Columbia, Canada
Clean Energy Research Centre, Faculty of Applied Science
Vancouver, Canada
1.1.–31.12.2010
Research area: Water management in fuel cells

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

Prof Uwe Nuss
Fachhochschule Offenburg
Offenburg, Germany
1.10.2010–31.1.2011
Research area: PV inverter control

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

PARTICIPATION IN ORGANISATIONS

acatech – Deutsche Akademie der Technikwissenschaften, Member

Alliance for Rural Electrification, Member

Bavaria California Technology Center (BaCaTec), Board of Trustees

Brennstoffzellen- und Batterie-Allianz Baden-Württemberg (BBA-BW), Member and Executive Committee

Bundesverband Kraft-Wärme-Kopplung (B.KWK), Member

Bundesverband Solarwirtschaft (BSW),
- *Arbeitskreis »Ländliche Elektrifizierung«, Member*

CAN in Automation (CiA), Member

CPV-Consortium, Board of Directors, Member

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

Deutscher Kälte- und Klimatechnischer Verein e. V. (DKV), Member

Deutscher Wasserstoff- und Brennstoffzellen-Verband e. V., Member

Deutsches Institut für Normung e. V. (DIN)
- *Fachnormenausschuss Heiz- und Raumlufttechnik (NHRS AA1.56) "Solaranlagen", Member*
- *Fachnormenausschuss Lichttechnik (FNL 6) "Innenraumbeleuchtung mit Tageslicht", Member*
- *Fachnormenausschuss Lichttechnik (FNL 21) "Spiegelmaterial für die Lichttechnik", Member*
- *Normenausschuss Bau (NABau) 00.82.00 "Energetische Bewertung von Gebäuden", Member*
- *Gemeinschaftsausschuss (NABauNHRS) "Energetische Bewertung von Gebäuden", Member*

Dii – Desertec Industrial Initivative, Associate Partner

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 TC312/WG1/WG2/WG3, Member*

European Academy, Institute for Renewable Energy (Bolzano/Italy), Member of Scientific Board

European Center for Power Electronics e. V. (ECPE), Member

European H2/FC Technology Platform, Member

European Photovoltaic Industry Association (EPIA), Associate Member

European Power Electronics and Drivers Association (EPE), Member

European Renewable Energy Research Centres Agency (EUREC), Member

European Solar Thermal Industry Federation (ESTIF), Member

Expertenkommission der Bundesregierung "Forschung und Innovation", Member

Fachausschuss Tageslicht der Lichttechnischen Gesellschaft (LitG), Member

Fachinstitut Gebäude-Klima (FGK)
- *Arbeitskreis "Expertenkreis Klimaschutz", Member*

PARTICIPATION IN ORGANISATIONS

Fachverband Transparente Wärmedämmung e. V., Member

FitLicht – Fördergemeinschaft innovative Tageslichtnutzung, Member

Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW) e. V.
- *Arbeitskreis "Photovoltaik", Co-operating Member*
- *Arbeitsgruppe "Oberschwingungen", Co-operating Member*

ForschungsVerbund Erneuerbare Energien (FVEE), Member

Fraunhofer-Allianz Bau, Member

Fraunhofer-Allianz Energie, Management and Spokesperson

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

Fraunhofer-Netzwerk Nachhaltigkeit, Member

Fraunhofer-Netzwerk Windenergie, Member

Fraunhofer Systemforschung Elektromobilität, Member

Fraunhofer-Themenverbund Werkstoffe und Bauteile, Member

Freiburger Verein für Arbeits- und Organisationspsychologie, Board of Directors

Fuel Cell Europe, Member

German Scholars Organization (GSO), President

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 Illumination CIE
- *TC 3-39 "Discomfort Glare from Daylight in Buildings", Member*
- *TC 3-4 "Climate-Based Daylight Modelling", Member*

International Electrotechnical Commission IEC
- *TC82 "Concentrator Modules", WG7, Member*
- *TC105 "Fuel Cell Technologies", WG 7/WG 11, Member*

International Energy Agency IEA, Member:
Solar Heating & Cooling Programme SHCP
- *Task 44 "Solar and Heat Pump Systems – Systems Using Solar Thermal Energy in Combination with Heat Pumps"*
- *Task 43 "Solar Rating and Certification Procedure – Advanced Solar Thermal Testing and Characterization for Certification of Collectors and Systems"*
- *Task 33/34 "Solar Heat for Industrial Processes"*
- *Task 37 "Advanced Housing Renovation"*
- *Task 38 "Solar Air-Conditioning and Refrigeration"*
- *Task 39 "Polymeric Materials for Solar Thermal Applications" Energy Conservation in Buildings and Community Systems Programme ECBCS*
- *Annex 47 "Cost Effective Commissioning", Energy Conservation Through Energy Storage Programme ECES*
- *Annex 18 "Transportation of Energy Utilizing Thermal Energy Storage Technology", Heat Pump Programme HPP*
- *Annex 32 "Economical Heating and Cooling Systems for Low Energy Houses"*
- *Annex 34 "Thermally Driven Heat Pumps"*

IEA Implementing Agreement Solar Power and Chemical Energy Systems SOLARPACES
- *Task I "Solar Thermal Electric Systems"*
- *Task III "Solar Technology and Advanced Applications"*

International Organization for Standardization ISO, TC180/SC4, Member

International Programme Committee of GADEST, Member

International Science Panel on Renewable Energies (ISPRE), Secretariat

Intersolar North America, Programme Committee, Chair

Kompetenzfeld Photovoltaik NRW, Member

Kompetenznetzwerk Brennstoffzelle NRW, Member

Leibniz-Institut für Kristallzüchtung IKZ, Advisory Board

Lichttechnische Gesellschaft, Member

M&EED Monitoring and Evaluation Working Group by Global Village Energy Partnership (GVEP) and European Union Energy Initiative (EUEI), Member

Mikrosystemtechnik Baden-Württemberg (MST-BW), Advisory Board

Scientific Commission to the ENI Science and Technology Award, Member

SEMI International, Board of Directors, Member

SEMI® Standards, Photovoltaic Equipment Interface Specification Task Force (PV-EIS), Member

SERIS, Advisory Board

Stiftung Solarenergie, Advisory Board

Symposium Photovoltaische Solarenergie, Scientific Advisory Board

VDI-Gesellschaft Technische Gebäudeausrüstung
- *Richtlinienausschuss 4706 "Kriterien für das Innenraumklima"*
- *Richtlinienausschuss 4650, Blatt 1 und Blatt 2*
- *Richtlinienausschuss 4645*
- *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 zu Energieeffizienz in Gebäuden, Founding Member

Verein Deutscher Ingenieure (VDI)
VDI-Gesellschaft Energietechnik
- *Fachausschuss "Regenerative Energien" (VDI-FA-RE), Member*

VMPA – Verband der Materialprüfämter e. V.
- *Sektorgruppe "Türen, Fenster und Glasprodukte", Member*

Weiterbildungszentrum WBZU "Brennstoffzelle", Board of Directors

Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW, Board of Trustees

TRADE FAIRS

Elektromobile Stadt
Stuttgart, Germany, 21.1.2010

25. Symposium Photovoltaische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 3.–5.3.2010

Battery Japan – 1st International Rechargeable Battery Expo
Tokyo, Japan, 3.–5.3.2010

FC Expo – 6th International Hydrogen & Fuel Cell Expo
Tokyo, Japan, 3.–5.3.2010

6. International Conference on Concentrating Photovoltaic Systems (CPV-6)
Freiburg, Germany, 7.–9.4.2010

HANNOVER MESSE
Hanover, Germany, 19.–23.4.2010

EXPO 2010
"Better City – Better Life"
Shanghai, China, 1.5.–31.10.2010

Les Rendez-Vous CARNOT
Lyon, France, 5./6.5.2010

20. Symposium Thermische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 5.–7.5.2010

World Hydrogen Energy Conference (WHEC)
Essen, Germany, 16.–21.5.2010

MS Wissenschaft 2010 – das Energieschiff
Germany-wide, 18.5.–7.10.2010

Entdeckungen/Discoveries
Mainau Island, Germany, 20.5.–29.8.2010

Intersolar
Munich, Germany, 9.–11.6.2010

Intersolar North America
San Francisco, USA, 13.–15.7.2010

25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC)
Valencia, Spain, 6.–9.9.2010

CLEAN TECH WORLD
Berlin, Germany 15.–19.9.2010

Tag der Energie
Berlin, Germany 24./25.9.2010

f-cell Forum
Stuttgart, Germany 27./28.9.2010

Glasstec / glass technology live
Düsseldorf, Germany 28.9.–1.10.2010

CONGRESSES, CONFERENCES AND SEMINARS

Fraunhofer ISE organised or co-organised the following congresses, conferences and seminars:

Sixth User Forum Thin-Film Photovoltaics (OTTI)
"Modules – Systems – Applications"
Würzburg, Germany, 8./9.2.2010

Workshop SiliconFOREST
"Fortschritte in der Entwicklung von Solarzellen-Strukturen und Technologien"
Falkau, Germany, 28.2.–3.3.2010

25. Symposium Photovoltaische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany 3.–5.3.2010

6th International Conference on Concentrating Photovoltaic Systems (CPV-6)
Freiburg, Germany, 7.–9.4.2010

5th European Conference PV-Hybrid and Mini-Grid (OTTI)
Tarragona, Spain, 29./30.4.2010

20. Symposium Thermische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, Germany, 5.–7.5.2010

Power Electronics for Photovoltaics (OTTI-Seminar)
Munich, Germany, 7./8.6.2010

6th PV Industry Forum, Intersolar
Munich, Germany, 7.–11.6.2010

Intersolar Europe Conference
"Solar Heat for Industrial Processes and Small Scale Power Co-Generation"
Munich, Germany, 9.6.2010

35th IEEE Photovoltaic Specialists Conference (PVSC)
Honolulu, USA, 20.–25.6.2010

Intersolar North America Conference
San Francisco, USA, 13.–15.7.2010

25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC)
Valencia, Spain, 6.–10.9.2010

5. Internationale Konferenz zur Speicherung Erneuerbarer Energien IRES 2010
Berlin, Germany, 22.–24.9.2010,

Fraunhofer-Energietage
"Energiekonzept Deutschland – Mit neuer Energie"
Berlin, Germany, 23./24.9.2010

Kick-Off Event "Netzintegration und Ladeinfrastruktur – Mobile Verbraucher im Kontext kommunaler Energieversorgung", Forum ElektroMobilität
Berlin, Germany, 6.10.2010

Fachforum "Netzferne Stromversorgung mit Photovoltaik" (OTTI)
Freiburg, Germany, 6./7.10.2010

FVEE-Jahrestagung 2010
"Forschung für das Zeitalter der erneuerbaren Energien"
Berlin, Germany, 11./12.10.2010

Solar Summits Freiburg – International Conference on Renewable and Efficient Energy Use
"Solar Mobility – Battery Systems, Fuel Cells and Biofuels for Sustainable Electromobility"
Freiburg, Germany, 15./16.10.2010

Brennstoffzellen- und Batterie-Allianz Baden-Württemberg (BBA-BW)
Workshop "Batterietechnologie"
Karlsruhe, Germany, 28.10.2010

KONGRESS, Forum ElektroMobilität
Berlin, Germany, 16./17.11.2010

Workshop on MWT Solar Cell and Module Technology
"A Complete Overview of Research Concepts and Innovations"
Amsterdam, Netherlands, 25.11.2010

DOCTORAL THESES

Jan Benick:
"High-Efficiency n-Type Solar Cells with a Front Side Boron Emitter", Albert-Ludwigs-Universität Freiburg, Freiburg, 2010

Jan Catoir:
"Entwicklung und Charakterisierung von Kathodenzerstäubungsverfahren für kristalline Silizium-Solarzellen" (Development and Characterisation of a Magnetron Sputtering Process for Crystalline Silicon Solar Cells), Universität Konstanz, Konstanz, 2010

Andreas Fell:
"Modelling and Simulation of Laser Chemical Processing (LCP) for the Manufacturing of Silicon Solar Cells", Universität Konstanz, Konstanz, 2010

Luca Gautero:
"Evaluation of Cost-Effective Technologies for Highly Efficient Silicon-Based Solar Cells", École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, 2010

Daniela Grote:
"Analysis of Silicon Solar Cells and their Measurement Methods by Distributed Circuit Simulations and by Experiment", Universität Konstanz, Konstanz, 2010

Wolfgang Guter:
"Optimierung von III-V basierten Hochleistungssolarzellen" (Optimisation of High Efficiency Solar Cells from III-V Compound Semiconductors), Universität Konstanz, Konstanz, 2010

Raymond Hoheisel:
"Charakterisierung und Optimierung von hocheffizienten III-V Weltraumsolarzellen: Strahlungsresistenz, Spektrum- und Temperaturabhängigkeit" (Characterisation and Optimisation of High-Efficiency III-V Solar Cells for Space: Radiation Resistance, Spectral and Temperature Dependence), Universität Konstanz, Konstanz, 2010

Joachim Jaus:
"Entwicklung von photovoltaischen Konzentratormodulen mit Fresnel-Linsen und reflektiver Sekundäroptik" (Development of Photovoltaic Concentrator Modules with Fresnel Lenses and Reflecting Secondary Optic), Albert-Ludwigs-Universität Freiburg, Freiburg, 2010

Martin Kasemann:
"Infrared Imaging Techniques for Crystalline Silicon Solar Cell Characterization and Production Control: What Photons Tell us about Solar Cells", Albert-Ludwigs-Universität Freiburg, Freiburg, 2010

Sinje Keipert-Colberg:
"Multikristalline Siliziumsolarzellen mit Siliziumoxid-Siliziumnitrid-Rückseitenpassivierung" (Back-Side Passivation of Multicrystalline Silicon Solar Cells with Silicon Oxide / Silicon Nitride), Christian-Albrechts-Universität, Kiel, 2010

Wolfram Kwapil:
"Alternative Materials for Crystalline Silicon Solar Cells – Risks and Implications", Universität Konstanz, Konstanz, 2010

Julia Melke:
"Study of the Ethanol Oxidation in Fuel Cell Operation Using X-Ray Absorption Spectroscopy and Electrochemical Methods", TU Darmstadt, Darmstadt, 2010

Emily Mitchell:
"Emitter-Wrap-Through, Rear-Side Contacting for Crystalline Silicon Thin-Film Wafer Equivalent Solar Cells", New South Wales University, Sydney, Australia, 2010

Gabriel Morin:
"Techno-Economic Design Optimization of Solar Thermal Power Plants", TU Braunschweig, Braunschweig, 2010

Simon Philipps:
"Analyse und Optimierung von III-V Solarzellen mittels numerischer Modellierung" (Analysis and Optimisation of III-V Solar Cells by Numerical Modelling), Universität Konstanz, Konstanz, 2010

Philipp Rosenits:
"Electrical Characterisation of Crystalline Silicon Thin-Film Material", Universität Konstanz, Konstanz, 2010

PROMOTION OF YOUTH

Fraunhofer ISE is also active in recruiting youth for scientific and engineering fields in particular. We organise ongoing numerous events in which our scientists actively partake. Through these, we strive to foster enthusiasm for renewable energy in today’s youth. Further, the activities offer young people the possibility to gain insight about educational training possibilities and employment at an early stage.

In 2010, Fraunhofer ISE participated in the Science Days in Rust. At the event, we presented exhibits, which were made at our Institute especially for demonstrative purposes. We offered young visitors the possibility to try out simple experiments dealing with photovoltaics and energy consumption. In co-operation with Solare Zukunft e.V., we participated in the show "Entdeckungen – Discoveries" on the Island of Mainau. Also as part of the co-operative effort, we set up a program whereby scientists from Fraunhofer ISE visited physics classes in schools, providing the chance for dialogue with the students. On Girls Day 2010 we again invited interested girls to our Institute and enabled them the chance to perform age-appropriate experiments in our laboratories. In 2010, we also participated in the "Kreativwoche" sponsored by the "Kulturakademie der Stiftung Kinderland" Baden-Württemberg as well as in the Freiburg Researcher Days ("Forschertagen Freiburg").

PATENTS

PATENTS GRANTED

"Transport device and method of transporting to-be-processed elements through a high-temperature zone"
Biro, Daniel; Wandel, Gernot; Lenz, Reinhard; Völk, Peter
CA 2,380,261 C

"Method and apparatus for drying the workpiece and/or keeping the workpiece dry during work with a liquid jet"
Kray, Daniel
CH 700 816 B1

"Circuit breaker for a solar module"
Burger, Bruno; Schmidt, Heribert
CN 101180781 B

"Solar cell module (for concentrating solar systems with multiple solar cells on an area with a metal-coated substrate) and method for its production"
Jaus, Joachim; Bett, Andreas; Bösch, Armin; Dimroth, Frank; Lerchenmüller, Hansjörg
DE 10 2005 035 672 B4

"Method for recrystallising layer structures by zone melting, device for carrying out said method and the use thereof"
Reber, Stefan; Eyer, Achim; Haas, Fridolin
DE 10 2005 043 303 B4, EP 1 924 724 B1, US 7,713,848 B2

"Process to recover high-purity silicon material from laser etching in polycrystalline form"
Mayer, Kuno; Hopman, Sybille; Kray, Daniel; Kolbesen, Bernd O.
DE 10 2006 003 605 B4

"Fuel cell module and its use"
Wolff, Andreas; Tranitz, Marco; Jungmann, Thomas; Oszcipok, Michael
DE 10 2006 048 860 B4

"Method for determining the base layer resistance of a semiconductor wafer e.g. multi-crystalline silicon wafer by an inductive measuring method"
Spitz, Meinrad; Rein, Stefan
DE 10 2007 040 650 B4

"Method for producing a metal structure on a surface of a semiconductor substrate"
Mingirulli, Nicola; Biro, Daniel; Schmiga, Christian; Specht, Jan; Stüwe, David
DE 10 2008 029 107 B4

"Method for transporting heat, transport system for a heat carrier and the use thereof"
Hermann, Michael; Gschwander, Stefan
DE 10 2008 048 655 B4

"Isolating circuit for inverters"
Burger, Bruno; Schmidt, Heribert
DE 10 2008 048 841 B3

"Method for light-induced galvanic pulsed deposition to reinforce metal contacts of solar cells, Apparatus for carrying out the procedure and its use thereof"
Radtke, Valentin; Bartsch, Jonas; Hörteis, Matthias
DE 10 2008 053 621 B4

"Method and device for simultaneous microstucturing and passivating"
Mayer, Kuno; Kray, Daniel
DE 10 2009 004 902 B3

"Method for removing material from solids and its use thereof"
Mayer, Kuno; Kolbesen, Bernd O.; Kray, Daniel; Hopman, Sybille
EP 1 979 122 B1

"Adsorber and its use in heat accumulators and heat pumps, or refrigeration"
Brovchenko, Ivan; Oleinikova, Alla; Geiger, Alfons; Schmidt, Ferdinand
EP 2 049 248 B1

"Inverter as well as procedure for transforming a DC voltage into an AC current or an AC voltage"
Schmidt, Heribert; Siedle, Christoph; Ketterer, Jürgen
EP 2 086 102 B1

"Proton-conducting polymer membrane and method for the production thereof to simultaneously remove the catalyst layers"
Hahn, Robert; Wagner, Stefan; Schmitz, Andreas
US 7,655,342

"System comprising a glazing element and a gas supply device"
Graf, Wolfgang; Rox, Rainer
US 7,774,997 B2

"Method for simultaneous recrystallization and doping of semiconductor layers"
Reber, Stefan
US 7,838,437 B2

"Device and method for continuous chemical vapour deposition under atmospheric pressure and use thereof"
Reber, Stefan; Hurrle, Albert; Schillinger, Norbert
ZL 200680034544.3

REGISTERED PATENT APPLICATIONS

"Method for local contacting and local doping of a semiconductor layer"
Preu, Ralf; Grohe, Andreas; Biro, Daniel; Rentsch, Jochen; Hofmann, Marc; Wolf, Andreas; Nekarda, Jan-Frederik
DE 10 2008 044 882 A1

"Method for measuring the luminescence radiation of a semiconductor structure"
Giesecke, Johannes
DE 10 2008 044 883 A1

"Method for light-induced galvanic pulsed deposition to reinforce metal contacts of solar cells, Apparatus for carrying out the procedure and its use thereof"
Radtke, Valentin; Bartsch, Jonas; Hörteis, Matthias
DE 10 2008 053 621 A1

"Thermopneumatic micro valve based on phase change material"
Lenz, Bettina; Bromberger, Kolja
DE 10 2008 054 220 A1

"Stacked solar cell with reflecting interlayer as well as assembly of this solar cell"
Niggemann, Michael; Zimmermann, Birger
DE 10 2009 019 937 A1

"Mixing device for fluids and its use as well as the mixing method"
Aicher, Dr. Thomas; Schaadt, Achim; Voglstätter, Christopher; Full, Johannes
DE 10 2009 019 938 A1

"Photovoltaic module with flat cell connector"
Wirth, Harry; Wagner, Hans-Ulrich; Kalmbach, Jens; Hirzler, Bernd; Strebel, Beat
DE 10 2009 023 901 A1

"Method for manufacturing a single-sided contact solar cell"
Hermle, Martin; Bivour, Martin; Reichel, Christian
DE 10 2009 040 670 A1

"Interface circuit"
Schmidt, Heribert; Burger, Bruno
DE 10 2009 051 186 A1

"Method for the production of mechanically prestressed solar cell composites and also a mechanically prestressed solar cell module"
Wirth, Harry
EP 2 154 728 A2

"Method for itemising the electrical consumption of a number of electrical consumers and device for the same"
Büttner, Markus
EP 2 237 212 A1

"Tunnel diodes from strain-compensated compound semiconductor layers"
Guter, Wolfgang; Dimroth, Frank; Schöne, Jan
EP 2 251 912 A1

"Metal-containing composition, process for producing electric contact structures on electronic components and also electronic component"
Hörteis, Matthias; Woehl, Robert; Glunz, Stefan; Filipovic, Aleksander; Schmidt, Daniel
WO 2010/003619 A1

"Photovoltaic device and method for producing a concentrator optical unit"
Nitz, Peter
WO 2010/012479 A2

"Open encapsulated concentrator system for solar radiation"
Löckenhoff, Rüdiger; Bett, Andreas; Wiesenfarth, Maike; Segev, Roy
WO 2010/012491 A2

"Solar cell and method for producing a solar cell"
Clement, Florian; Biro, Daniel; Menkö, Michael; Kubera, Tim
WO 2010/015310 A3

"Method for determining the recombination properties at a measuring section of a measuring side of a semiconductor structure"
Kasemann, Martin; Hermle, Martin; Granek, Filip
WO 2010/022874 A1

"Solar cell and solar cell module with one-sided connections"
Biro, Daniel; Mingirulli, Nicola; Clement, Florian; Preu, Ralf; Woehl, Robert
WO 2010/022911 A2

"Method for determining the excess charge carrier lifetime in a semiconductor layer"
Rosenits, Philipp; Roth, Thomas; Glunz, Stefan
WO 2010/022922 A1

"Measuring method for a semiconductor structure"
Würfel, Peter; Schubert, Martin; Kasemann, Martin; Warta, Wilhelm
WO 2010/022962 A1

"Fuel cell arrangement and method for the production thereof"
Zschieschang, Eva; Gerteisen, Dietmar; Zedda, Mario; Ackermann, Volker
WO 2010/022965 A1

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LECTURE COURSES AND SEMINARS

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Vorlesung WS 10/11
Hochschule Offenburg
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Brisa Ortiz
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Seminar SS 10 and WS 10/11
Universität Kassel
European Master in Renewable Energy

Dr Jens Pfafferott
"Solares Bauen"
Präsenzveranstaltung SS 10 und WS 10/11
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Dr Ralf Preu
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"Photovoltaik I" Vorlesung WS 09/10
"Photovoltaik II" Vorlesung SS 10
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"Photovoltaische Systemtechnik"
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Prof Eicke R. Weber, Dr Werner Platzer,
Dipl-Ing (FH) Korbinian Kramer
"Solarthermie"
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In addition to the teaching activities at colleges and universities mentioned here, the scientists at Fraunhofer ISE regularly carry out practically oriented workshops and courses of further education for people from the finance sector and industry. We offer seminars and workshops on silicon technology in the series "PV Training", for example; or in the OTTI seminar "Off-Grid Power Supply" we provide our expertise on the products, planning and construction of remote electrical power systems.

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CONFERENCES AND TRADE FAIRS IN 2011 WITH FRAUNHOFER ISE PARTICIPATION:

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Boston, USA,10./11.2.2011

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

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Tokyo, Japan, 2.–4.3.2011

40. Jahrestagung der Gesellschaft für Umweltsimulation
Stutensee, 30.3.–1.4.2011

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HANNOVER MESSE
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Workshop PV-Module Reliability
Berlin, 5./6.4.2011

International Sorption Heat Pump Conference ISHPC11
Padua, Italy, 6.–8.4.2011

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

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

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Freiburg, Fraunhofer ISE, 1.–3.6.2011

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San Francisco, USA, 12.–14.7.2011

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5th European Weathering Symposium EWS
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Stuttgart, 26./27.9.2011

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Berlin, Flughafen Tempelhof, 30.9.–3.10.2011

4th International Conference on Solar Air-Conditioning
Larnaca, Cyprus, 12./13.10.2011

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