Fraunhofer ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2009

Cover:
View into the entrance of Fraunhofer ISE in Freiburg. A 7.5 kW$_p$ photovoltaic array is integrated into the saw-tooth roof of the atrium. Photovoltaic modules with a total area of more than 200 m^2 are integrated into roof and façade elements, and contribute to the electricity supply for the Institute. The energy concept for the building is based on energy conservation and rational use of energy (© Bernd Lammel, Berlin).

FOREWORD

2009 was characterised by the largest global and financial crisis in 70 years. In spite of the short term ease in the energy supply and prices due to the crisis, the importance of a comprehensive global transition in energy supply and use has become even more evident. The new German government has also clearly committed itself to renewable energies. In the coalition agreement, the goal is stated in black and white: "Renewable energies are to take over a dominating portion of the energy supply." This will hopefully show up in the national energy concept and in the 6th Energy Research programme, both of which are to be worked on and approved in 2010. The goal remains to markedly increase the energy efficiency in buildings, in the transportation sector and in production as quickly as possible and to provide the rest of the energy still required from renewable sources.

The Fraunhofer Institute for Solar Energy Systems ISE is well equipped to meet this challenge. Our Institute offers a wide range of innovative technologies in the areas of buildings ("Zero Energy House"), transportation ("E-Mobility") and distribution systems ("Smart Grids"), solar electricity and heat production (photovoltaics/solar thermal) as well as hydrogen and fuel cell technology. Due to the innovative strength and the untiring commitment of our staff, presently numbering over 900, we were able to increase our annual operating budget in 2009 despite the prevailing economic and political conditions at this time. As compared to 2008, the 2009 Operating Budget increased by more than 17 per cent up to 47 million euros (55 million including investments). Our successful participation in the Federal Government's economic stimulus packages, launched in 2009, contributed significantly to this very satisfying result.

After a scientific career of 28 years at Fraunhofer ISE, Prof Dr Volker Wittwer retired as our Deputy Director in June 2009. We are looking forward to continuing to work with him in his future role as Expert Consultant to Fraunhofer ISE. Two experienced department heads, Dr Andreas Bett of "Materials – Solar Cells and Technology" and Dr Hans-Martin Henning of "Thermal Systems and Building Technology", succeed him in the position of Deputy Directors.

In 2009, Gerhard Stryi-Hipp joined the staff at Fraunhofer ISE, taking over two areas of responsibility at once. He is the group leader of "Thermal Collectors and Applications" and also heads the new field "Energy Policy" covering the area of political consultation on the national and international level.

Dr Werner Platzer is responsible for our newly founded business area "Solar Thermal Technology". Since 2008, he heads the department "Materials Research and Applied Optics" at Fraunhofer ISE. We created a new structure within the groups of the Institute by appointing Team Leaders. Thus we encourage our young staff members to assume responsibility for their team already at an early stage in their career.

An exceptional honour was accorded to Prof Dr Adolf Goetzberger, founder of Fraunhofer ISE. He was distinguished for his life's work by the European Patent Office. At a festive ceremony in Prague's castle "Hradschin", he received the prize of "Inventor of the Year 2009".

At the 24th European Photovoltaic Solar Energy Conference and Exhibition, Dr Andreas Bett, Department Head of "Materials – Solar Cells and Technology" and Deputy Director of the

Institute was bestowed with the renowned Becquerel Prize. With this high-ranking award, he was honoured by the European Commission for his pioneer work on the development of photovoltaic concentrator technology.

For the development of Micronal® PCM, Prof Dr Volker Wittwer and Dr Peter Schossig, together with Dr Ekkehard Jahns (BASF), were among the three finalists in the running for the 2009 German Future Prize. Their innovation is based on microencapsulated latent heat storage or phase change materials (PCM) that can be incorporated into building materials. PCM has the capability to absorb heat from the environment and to release it again when needed in order to stabilize the room temperature.

In our research laboratories, excellent results and new records were again achieved in 2009. A new world record efficiency for III-V multi-junction solar cells on a germanium substrate was reached at the beginning of 2009. Dr Andreas Bett and Dr Frank Dimroth with their team achieved for the first time an efficiency of 41.1 per cent for the conversion of sunlight into electricity. The sunlight was concentrated 450 times and focused onto a small 5 mm^2 solar cell.

At 99.03 per cent world record efficiency, we once again surpassed our own world record for our PV inverters with silicon carbide components. By implementing new components and improved switching technology, Prof Dr Bruno Burger and his team were able to reduce the losses by one-third as compared to their own best value.

For their exceptional scientific work, Dr Daniel Biro, Dr Stefan Reber and Prof Dr Roland Schindler each received Excellence Grants from the Fraunhofer-Gesellschaft in 2009.

We could also successfully continue and even expand our national and international sites, spin-offs and co-operations this year. Our branches in Germany, the Laboratory and Service Centre LSC in Gelsenkirchen and the Fraunhofer Centre for Silicon Photovoltaics CSP in Halle, founded jointly with the Fraunhofer IWM, as well as the Technology Centre for Semiconductor Materials THM in Freiberg, have effectively continued and expanded their work.

In February 2009, the Fraunhofer ISE spun off yet another company called "SolarSpring". This start-up will produce solar-driven systems for water treatment and desalination and bring them to the market. They concentrate on decentralised applications. The membrane distillation systems developed at Fraunhofer ISE are used, for example, for the desalination of sea and brackish water.

Jointly with the Fraunhofer Institute for Systems and Innovation Research ISI in Karlsruhe, we founded the research group "Renewable Energy Innovation Policy". The Freiburg part is led by Dr Thomas Schlegl. The goal of this cooperation is to connect technology development and applied research with economic system analysis and innovation research.

Our TestLab Solar Thermal Systems at Fraunhofer ISE could be markedly expanded in 2009. Now, even more comprehensive measurement and testing facilities for solar collectors are available. These include several new trackers and a new hailstone test stand. With support from the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU), we have built up the Photovoltaic Module Technology Centre (MTC). The new facility provides a unique variety of experimental and analytic methods and thus creates a bridge between the developments in the laboratory and industrial production technology.

In 2009, the Fraunhofer Center for Sustainable Energy Systems CSE in Boston inaugurated its laboratory for PV modules. Numerous guests, including the German Ambassador Klaus Scharioth, were present at the ceremony. Since 2008, scientific researchers from Fraunhofer ISE are closely cooperating with the scientists from Fraunhofer CSE as well as from the Massachusetts Institute of Technology MIT, offering European expertise to the rapidly expanding market for renewable energies in the United States.

On the international level, together with the VDE Institute and the Solar Energy Research Institute of Singapore SERIS, we have founded the first test and certification centre for solar PV modules in South East Asia. The new VDE-ISE Pte. Ltd. – New Energy Technology (NET) offers a wide range of services, from the certification of solar modules and module components following international standards to lifetime and efficiency measurements including safety tests.

As representative for the Fraunhofer-Gesellschaft, I signed a Memorandum of Understanding with the leaders of the Masdar City project in spring 2009. Our Institute, together with the Fraunhofer Institutes for Industrial Engineering IAO and for Building Physics IBP, will serve as advisors during the design and construction of this ecological, self-sufficient model city in Abu Dhabi. Consulting and support in the areas of sustainable city development and building planning as well as photovoltaic systems are in the focus of our co-operation.

At this point, I would like to reference some upcoming events. In 2010, we will continue with the international congress series "Solar Summits". The theme of this year's scientific conference will be "Solar Mobility – Batteries, Fuel Cells and Biofuels for Sustainable Electromobility". We invite scientists and entrepreneurs worldwide to participate in this event to be held in Freiburg.

In the area of concentrator technology, a top-class scientific event will take place in Freiburg. The International Conference on Concentrating Photovoltaic Systems (CPV-6) is to be held on 7–9 April 2010. Over 120 scientists from 22 countries will report on the state-of-the-art technology. Accompanying the conference for the first time, companies from the industry will be present to provide information on market data and products. We look forward to welcoming you to this event in Freiburg.

In addition, the new "Master Online Photovoltaics" program will begin for the first time in the summer semester 2010. The goal is to provide extra occupational training and further education to specialists for the photovoltaic market. Fraunhofer ISE plays an instrumental role in setting up and carrying out this course of study at the University of Freiburg (www.pv-master.com).

To conclude my review of 2009 and the brief outlook for 2010, 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. As in the past years, your continuous support and sustained co-operation have made possible the positive, further development of our Institute.

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

ORGANISATIONAL STRUCTURE

The organisational structure of Fraunhofer ISE has two parallel, mutually complementary main components: Scientific departments and a grouping according to business areas. The scientific departments of the Institute are responsible for the research and development (R & D) in the laboratories, project work and 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.

Eicke R. Weber Hans-Martin Henning 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 and technical building components, 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)
- guest member of the Fraunhofer Group "Light & Surfaces"
- co-ordination of the Fraunhofer Innovation Topic of "Microenergy Technology", in the context of "Perspectives for Tomorrow's Markets"

International Clients and Co-operation Partners

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

External branches and Co-operations

The Fraunhofer ISE Laboratory and Service Centre LSC in Gelsenkirchen, in the State of North Rhine-Westphalia (NRW), has existed since 2000 and is 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 laboratory offers the simulation and optimisation of in-line processes, the development of new processes and structures for solar cells and research of large-area heterojunction solar cells of amorphous and crystalline silicon. LSC Gelsenkirchen also offers training sessions on characterisation procedures and solar cell technology.

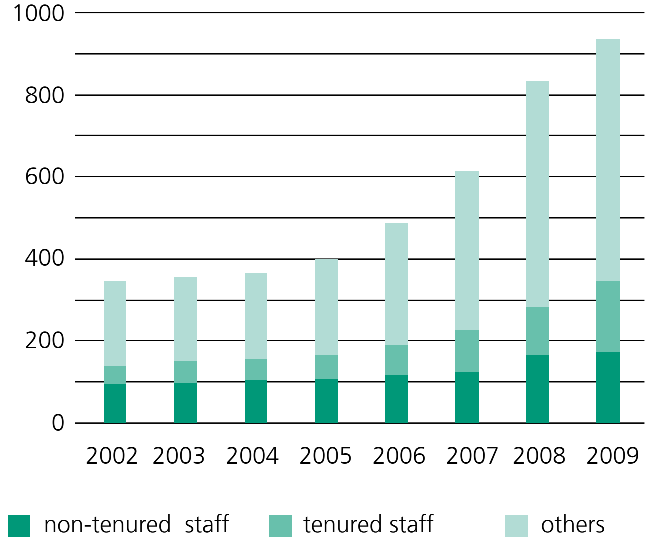
The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle/Saale, was founded in 2007. It is operated jointly by the Fraunhofer Institute for Mechanics of Materials IWM, Freiburg and Halle, and Fraunhofer ISE. In Halle, a centre for crystallisation and materials analysis was established, in which targeted research and development on silicon materials is conducted together with industrial partners. Beyond this, concepts for silicon thin-film cells and module integration are being developed. The Peak Cluster proposal "Solarvalley Mitteldeutschland" was co-ordinated by Fraunhofer CSP and consists of a group of about 40 partners from industry, research and education. This proposal was one of the five selected winners in a German-wide competition sponsored by the Federal Ministry for Education and Research (BMBF). Over the next five years, joint research shall be carried out with the goal of grid parity 2015.

The Fraunhofer Center for Sustainable Energy Systems CSE in Boston was founded in 2008. At CSE, know-how and technology for renewable energy that is already established in Europe is to be further adapted and introduced to the American market. The activities will concentrate on solar technology and energy-efficient building. The work is carried out in close co-operation between researchers from Fraunhofer ISE, Fraunhofer CSE and the Massachusetts Institute of Technology MIT.

The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, represents a co-operation between Fraunhofer ISE and the Fraunhofer Institute for Integrated Systems and Device Technology IISB in Erlangen. THM supports companies in research and development on materials preparation and processing of 300 mm silicon, solar silicon and III-V semiconductors. Beyond this, THM offers analytical, characterisation and testing services for production by industrial partners.

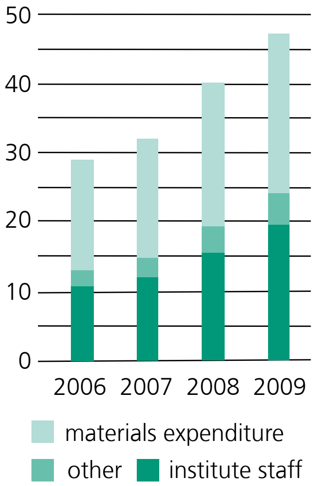
The financial structure of the Fraunhofer-Gesellschaft distinguishes between the operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. In addition to the expenditure documented in the graph, the Institute made investments of 7.7 million euros in 2009 (not including investments for building construction and the economic stimulus programme).

Personnel

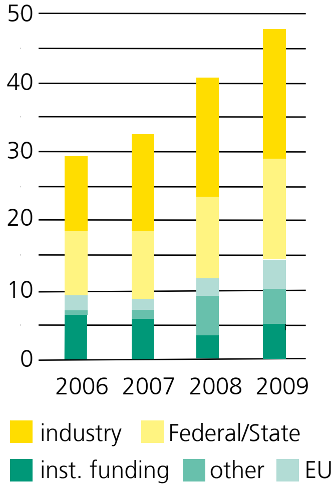


On 31 December 2009, a total of 936 staff members were employed at Fraunhofer ISE. Of these, 99 doctoral candidates, 112 undergraduate students, 53 trainees, 5 apprentices and 229 scientific assistants as well as 93 further staff (guest scientists) support the work in the research projects and thus contribute significantly to the scientific results obtained. In this way, Fraunhofer ISE makes an important contribution toward educating researchers in this important field of work.

Expenditure million euros



Income million euros



R & D HIGHLIGHTS OF 2009

ENERGY EFFICIENT BUILDINGS AND BUILDING TECHNOLOGY

- Start of the heat pump monitoring project "WP Monitor" with heat pump manufacturers and energy suppliers
- Successful demonstration of the mature gaschromic system technology
- Efficient tools for diagnosing and analysing the building operation
- Efficient composite materials – zeolite-metal sponge for compact adsorption heat pumps
- Energy concept for plus energy single family houses from the company "Sonnenkraft"
- System for investigating the stability of adsorbent-metal composites
- Simulation procedure for identifying the relevant thermal and material transport parameters (diffusion, thermal conductivity, heat transfer) for adsorbent-metal composites
- Development and validation of a procedure for dynamically determining daylighting glare
- Determination of the solar energy potential on roofs based on laser scan data

APPLIED OPTICS AND FUNCTIONAL SURFACES

- Projection screen for 3-D displays with 50" screen diagonal manufactured with interference lithography
- First active phase stabilisation for interference lithography with three waves realised
- Development of cost-effective silver-based transparent electrodes

SOLAR THERMAL TECHNOLOGY

- Dynamic efficiency measurements for CSP collectors enabling the angular dependency of the optical efficiency to be determined
- Development of a model for optimising the technology and economics of solar thermal power plants using a detailed coupled simulation for the solar field and the block-unit power station
- New solar collector with static reflector for high efficiencies at operating temperatures > 100 °C
- Improved photovoltaic-thermal collector for simultaneous production of electricity and heat
- Determining the energy saving potential of a solar combined heat and power plant in stand-alone operation as compared to using large diesel generators
- Founding the company "SolarSpring" in the area of solar thermal driven desalination systems based on membrane distillation

SILICON PHOTOVOLTAICS

- Crystallisation of first multi-crystalline silicon block (for feedstock evaluation) with a weight of 15 kg
- 17.1 % efficiency for a large area (156 x 156 mm²) MWT solar cell from multi-crystalline silicon at the PV-TEC demonstration level
- 18.8 % efficiency for a screen printed EWT solar cell
- 20.6 % efficiency for solar cell with printed front and back-surface contacts and laser-fired contacts
- 23.5 % efficiency for an n-type silicon solar cell with a boron front-surface emitter
- 18.2 % efficiency for a large area (148 cm²) n-type solar cell with a screen printed aluminium back-surface emitter
- 18.5 % efficiency for an a-SiC/c-Si heterojunction solar cell on p-type silicon
- 20.6 % p-type silicon solar cell with contacts of deposited nickel (Ni-plating and Ag galvanisation) and laser ablation of anti-reflection coating
- High-rate plasma-enhanced chemical-vapor-deposition (PECVD) process for aluminium-oxide layers demonstrated
- 18.6 % efficiency for a MWT-Si concentrator solar cell with 1 x solar radiation (C=1) and 19.5 % for 6 x solar radiation (C=6)
- 6.9 % efficiency for fluorescent collector system
- First time increase in the short circuit current of silicon solar cell through an upconversion layer under exposure to white light

- Successful demonstration of a edge-sealed laminate-free PV module with 16 cells
- Metallic precipitates identified as cause for the reverse-bias breakthrough in silicon solar cells
- Building up the Photovoltaic Module Technology Center (MTC)

ALTERNATIVE PHOTOVOLTAIC TECHNOLOGY

- 41.1 % world record efficiency for a III-V concentrator solar cell with 454 x solar radiation
- 28.9 % efficiency for multi-quantum well GaAs solar cell with 297 x solar radiation
- 29.6 % efficiency for concentrator module under real operating conditions
- Indoor concentrator module measurement stand available
- 5.4 % efficiency for organic solar cell
- 5 % efficiency over the active area for dye solar cell module (30 cm x 30 cm) sealed with glass frit

RENEWABLE POWER GENERATION

- 99.03 % world record efficiency for PV inverter using silicon carbide JFET transistors from the company "SemiSouth"
- Coordination of the Fraunhofer Group project to develop innovative battery systems for electric vehicles
- Development of reliable algorithms for determining charging state and age of lithium batteries
- Development of concept for sustainable rural electrification (in South East Asia) based on renewable energies
- Involved in area of electric mobility: determining the potential for the integration of electric vehicles in fleets, developing intelligent control concepts for a balanced load, storage and energy management
- Smart Metering concept for Smart Grids: InnoNet co-operative project DEMAX (Dezentrales Energie- und Netz MAnagement mit fleXiblen Stromtarifen), innovative energy management and communication systems, where decen-tralised suppliers and loads from the commercial and private sector can participate in the energy market

HYDROGEN TECHNOLOGY

- Planar fuel cell in multi-layer ceramic realised
- Reformer fuel cell system: electricity generation from bioethanol
- HT-PEM fuel cell system up to 1 kW_{el} successfully tested
- 50-channel impedence measurement system for the spatially resolved characterisation of fuel cells put into operation
- 1 kW vanadium redox flow battery constructed and put into operation
- Successful operation of a commercial gas burner using heating oil vapour from a patented catalytic oil evaporator
- Mobile, fully automated reformer fuel cell system to generate electricity with bioethanol presented at the Hannover Trade Fair
- Fluid gas reformer integrated into a mobile electrical power supply system with a high-temperature fuel cell (SOFC) and put in operation

SERVICE UNITS

- CalLab PV Cells: significantly reduced uncertainty in the calibration of solar cells after issuance of the accreditation as calibration laboratory according to ISO 17025 by the German Calibration Service (Deutscher Kalibrierdienst DKD).
- Expansion of the battery testing laboratory: tests up to 250 kW now possible
- Worldwide modern, extremely precise tracker put into operation (e.g. for IAM measurements on solar collectors)
- New system test stand for solar thermal systems put into operation
- New hail test for PV modules and solar thermal collectors
- New mechanical load test for PV modules
- Test stand on Grand Canary for testing PV modules under maritime weather conditions put into operation
- New test chamber for simultaneous weathering of entire PV modules and collectors under UV radiation and higher humidity at high temperatures
- Extremely sensitive test facilities for temperature-dependent measurements of the permeation of atmospheric gases (O_2, N_2, H_2O, CO_2, Ar) through barrier layers.

AWARDS AND PRIZES

1

Patrick Dupeyrat received a poster award at the 18th International Photovoltaic Science and Engineering Conference (PVSEC-18) in Calcutta, India in January 2009. His poster was entitled "Analysis of a Hybrid PV-Thermal Collector Concept".

Sebastian Rau and **Dr Tom Smolinka** with their colleagues Roderick Fuentes and Prof John Weidner received the E.ON Research Award 2008 of the E.ON International Research Initiative for the project "Nano-Structured Electrodes for High Efficient Solar Hydrogen Production by Means of PEM Water Electrolysis" in April 2009.

Prof Dr Adolf Goetzberger, Founder of Fraunhofer ISE, was honoured for his lifetime achievements by the European Patent Office in April 2009. At a festive ceremony at Prague's castle Hradschin, he received the 2009 European Inventor of the Year Award.

Prof Dr Adolf Goetzberger and **Prof Dr Volker Wittwer** received the Spirit of Energy in May 2009, marking the first time that pioneers of the OTTI-Symposium Thermische Solarenergie were honoured.

Prof Dr Eicke R. Weber received the Electronics and Photonics Division Award from the Electrochemical Society ECS, San Francisco in June 2009.

Marc Steiner was distinguished for his Diploma thesis entitled "Minimierung von seriellen Widerstandsverlusten in III-V-Solarzellen mit Hilfe einer SPICE-Netzwerksimulation" (Minimising series resistance losses in III-V solar cells with a SPICE simulation). In June 2009 at the annual meeting of the Fraunhofer-Gesellschaft in Munich, he received the 2nd Hugo-Geiger-Preis.

Raymond Hoheisel received the Young Researcher Award at the 34th IEEE PVSEC for his presentation on "Analysis of Radiation Hardness of Rear-Surface Passivated Germanium Photovoltaic Cells" in June 2009. At the same conference, **Nicola Mingirulli** received the Best Poster Award in the "Crystalline Silicon Technologies" category for his poster on "Hot-Melt Inkjet as Masking Technology for Back-Contacted Cells".

Arno Bergmann, Timo Kurz and **Dietmar Gerteisen** were awarded the Schönbein-Medaille in bronze for their poster on "Dynamic Modelling of CO Poisoning in PBT HTPEM Fuel Cells" at the European Fuel Cell Forum in Lucerne, Switzerland in June/July 2009.

Dr Lisbeth Rochlitz, Timo Kurz and **Dr Thomas Aicher** received a poster award at the 17th European Biomass Conference in Hamburg in July 2009. The title of their poster was "Bio-Ethanol Reformer with HT-PEM Fuel Cell for Domestic Combined Heat and Power Generation".

Dr Andreas Bett, Department Head of "Materials – Solar Cells and Technologies" and Deputy Director of the Institute received the Becquerel Prize from the European Commission at the 24th European Photovoltaic Solar Energy Conference and Exhibition. Also on the occasion of the 24th European Photovoltaic Solar Energy Conference and Exhibition, **Dr Wilhelm Warta** received a poster award in the category of "Wafer-Based Silicon Solar Cells and Material Technology" for his poster "Precise Measurement of Solar Cell Performance in Production".

Prof Dr Bruno Burger and **Dirk Kranzer** received the Solar Industry Award 2009 in the category of "Industry Development" at the 24th European Photovoltaic Solar Energy Conference.

2

Prof Dr Eicke R. Weber was named an honorary member of the IOFFE Physical-Technical Institute of the Russian Academy of Sciences in St. Petersburg in October 2009.

Martin Keller received the Kulturpreis Bayerns for his Diploma thesis on "Design der Oberflächentextur einer Dünnschichtsolarzelle mithilfe statistischer Versuchsplanung" (Design of the surface texture of a thin-film solar cell using statistical experimental design) in October 2009.

Sebastian Burhenne received the IMTECH-Hermann-Rietschel-Preis in October 2009. His Master Thesis entitled "Simulationsmodelle zur Energieoptimierung des Gebäudebetriebs" (Simulation models to energetically optimise the building operation) took third place.

Dr Jan Wienold was honoured by the Hochschulgemeinschaft für Lichttechnik at the Universität Karlsruhe for his dissertation "Daylight Glare in Offices" in November 2009.

Benjamin Knödler received the E.ON Westfalia Weser Energy Award 2009 for his Diploma thesis "Modellbasierte Ladezustandsbestimmung bei Lithium-Ionen Batterien mit Kalman-Filtern" (Model-based state-of-charge determination for lithium-ion batteries with Kalman filters) in November 2009.

Prof Dr Bruno Burger, Dirk Kranzer, Florian Reiners and **Christian Wilhelm** received the Special Prize 2009 of the Future Prize from the Stiftung Ewald Marquardt, bestowed by Prof Bullinger, the President of the Fraunhofer-Gesellschaft. The three Fraunhofer researchers were distinguished for their work on "Kompakte Photovoltaik-Wechselrichter mit höchstem Wirkungsgrad" in Donaueschingen.

Karl-Anders Weiß was distinguished by the magazine "Desktop Engineering" within the framework of the Change the World Challenge. His contribution entitled "New Solar Collector Materials Modelled with COMSOL Multiphysics" occupied second place in the "Simulations that Change the World" category in December 2009.

Steffen Jack received 2nd place of the Tiburtius Prize from the Berlin universities for his Masters thesis on "Simulationsgestützte Qualifizierung neuer Konzepte zur Gestaltung von thermischen Solarkollektoren auf Polymerbasis" (Simulation-supported qualification of new concepts for the design of thermal solar collectors on a polymer basis).

Prof Dr Volker Wittwer and **Dr Peter Schossig** from Fraunhofer ISE and Dr Ekkehard Jahns of BASF were one of the three finalists for the German Future Prize 2009 for their joint work on Micronal® PCM, the microencapsulated latent heat storage for incorporation in building materials. With his prize for technology and innovation, the German President honours researchers and developers who invent new products as a result of excellent research and bring them successfully on the way into the market.

1 *Prof Dr Adolf Goetzberger, winner of the "2009 European Inventor of the Year" in the category "Lifetime Achievements" and Alison Brimelow, President of the European Patent Office (EPA) at the Awards Ceremony in Prague on 28 April 2009.*

2 *Bestowal of the Becquerel Prize at the 24th European Photovoltaic Solar Energy Conference and Exhibition, Dr Armin Räuber, Prof Dr Joachim Luther, prize winner Dr Andreas Bett, Prof Dr Adolf Goetzberger, Prof Dr Wolfram Wettling (from left to right).*

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: 16th November, 2009

BUILDING EFFICIENTLY WITH THE SUN

ENERGY-EFFICIENT BUILDINGS AND TECHNICAL BUILDING COMPONENTS

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 locally regenerative sources of energy are used 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 after 2019, new buildings 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. On the other hand, corresponding concepts must also be developed for the existing building stock and be applied on a widespread basis.

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, equip 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 in a broad scope 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 question concerning energy and user comfort. In doing so, we apply the most modern simulation procedures, which we develop further ourselves if necessary. Practical implementation of quality control plays an important role, which we achieve by accompanying and analysing demonstration buildings and programmes, and also by carrying out comprehensive field tests and monitoring campaigns.

Our work on the building envelope already has a long history concerning 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. Here, we are developing processes and systems based on phase-change materials for lightweight buildings and are working intensively on 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 heat, 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.

ENERGY-EFFICIENT BUILDINGS AND TECHNICAL BUILDING COMPONENTS

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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 correct, the performance of individual building components. Measures of this type, which are implemented at relatively low investment cost, can achieve significant savings in energy consumption and costs. Both the development and also the implementation of new procedures for energy-efficient operation management and control thus represent important fields of our work.

In collaboration with architects, professional planners and industrial representatives, we develop the buildings of tomorrow. In doing so, we follow an integrated planning approach, optimising concepts with respect to economic viability, energy efficiency and user comfort. Our approaches 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.

For their development of Micronal® PCM, Prof Dr Volker Wittwer and Dr Peter Schossig from Fraunhofer ISE and Dr Ekkehard Jahns from BASF were jointly nominated for the "Deutscher Zukunftspreis 2009" (German Future Prize). In 1999, the researchers started to develop micro-encapsulated phase-change materials (PCM) to store latent heat in building applications. They identified extremely pure paraffin wax as a suitable storage material for latent heat. The wax droplets are encapsulated in small, hollow, acrylate spheres with dimensions of a few micrometres. The resulting micro-capsules can be easily incorporated into building materials such as mortar, plaster and wood and are very robust: Construction materials containing Micronal® PCM can be used just like conventional materials – holes can be drilled or nails can be hammered into them without causing any problems.

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OUTDOOR EXPOSURE OF PV MODULES UNDER EXTREME CLIMATIC CONDITIONS

Manufacturers of solar modules currently give performance guarantees for 20 years and more. This is possible only because relevant experience on service lifetime is available for the materials used. Anyone who wishes to apply alternative, less expensive materials has difficulties in assessing their reliability. In order to create new opportunities in this field, we are developing an accelerated aging test for solar modules and are setting up outdoor exposure sites at locations with extreme climatic conditions.

Claudio Ferrara, Markus Heck, **Michael Köhl**, Daniel Philipp, Karl-Anders Weiß, Hans-Martin Henning

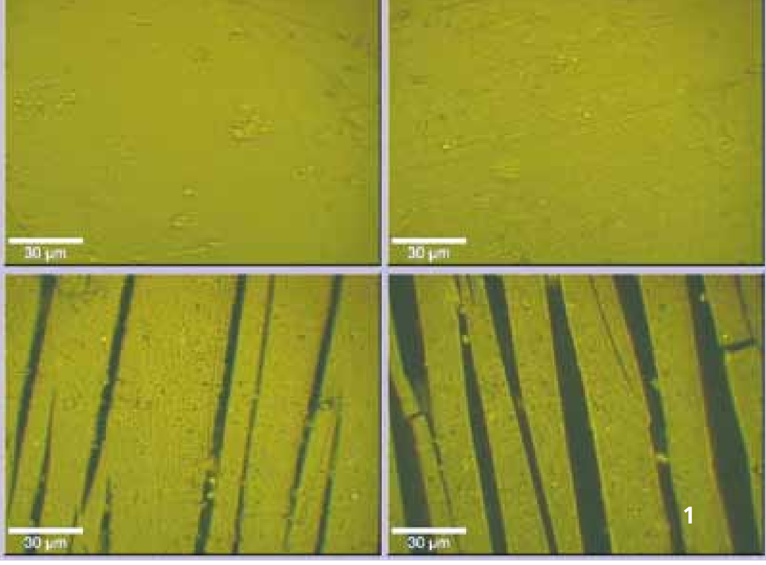
1 *Two examples of our outdoor exposure stations: left – Pozo Izquierdo, Gran Canaria, right – Zugspitze, Germany.*

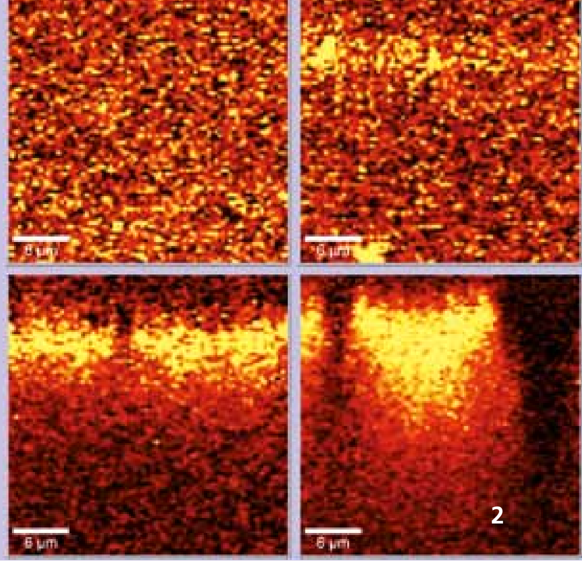
Materials and components to convert solar energy are weathered mainly by the following factors: Ultraviolet radiation, mechanical loads caused by snow and wind, pollutants (particularly salt), internal stresses resulting from different coefficients of thermal expansion and permeation of water and oxygen.

It is difficult to combine all of these weathering influences realistically in accelerated laboratory tests to imitate their interaction in sample aging. Exposure under natural conditions is thus mandatory to validate results of simulation and accelerated aging tests. Extreme climates expose weaknesses more quickly, on the one hand, and on the other hand, allow the test samples to be assessed for these special climatic conditions.

To this purpose, we operate outdoor exposure stations in arid, tropical, alpine and urban conditions, with urban conditions serving as a reference. Recently a further test facility was established in co-operation with the Instituto Tecnológico de Canarias (ITC), which features high wind loads, very dusty conditions and a maritime atmosphere promoting corrosion. We will test PV modules, solar-thermal collectors and materials for applications in maritime climates there.

The cluster project on “Reliability of PV Modules” is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).





INVESTIGATION OF AGING AND CHARACTERISATION OF POLYMERS

Resistance to weathering is an essential requirement for polymers to be used in the solar industry. We have systematically investigated the aging performance of polymer materials with different stabilisation systems in outdoor exposure and accelerated aging tests. Beyond this, the suitability of material characterisation methods such as high-resolution Raman microscopy and other non-destructive approaches was analysed.

Thomas Kaltenbach, Michael Köhl, Cornelia Peike, **Karl-Anders Weiß**, Hans-Martin Henning

1 *Microscope images of the surface of PP homopolymer samples after 0, 20, 40 and 60 weeks of outdoor exposure in Arizona. The progress of crack formation on the surface can be clearly followed.*

2 *Raman microscopic depth profiles in PP homopolymer after 0, 20, 40 and 60 weeks of outdoor exposure in Arizona (cf. Fig. 1). Depths down to 30 µm below the surface were investigated. Changes in the material begin to be clearly evident after 20 weeks. After 40 weeks, the formation of cracks can also be recognised.*

The resistance of solar energy systems to weathering is determined essentially by the materials used. This application presents a particular challenge to polymers. If they are to be applied in solar energy systems, it is imperative to know and analyse the effect of individual factors such as UV radiation, humidity and temperature and their behaviour over time.

In a systematic investigation, we have weathered and analysed samples of polypropylene (PP), polyamide (PA) and polycarbonate (PC) with different stabilising and filling materials, with or without optically selective coatings. Some of the samples were regularly characterised over a period of up to 100 weeks during outdoor exposure in Arizona, USA. Samples of the same type were subjected to indoor accelerated aging tests and experienced nine different temperature and humidity levels during simultaneous exposure to UV radiation. The samples were characterised by non-destructive methods such as determining the carbonyl index (by infrared spectroscopy), colour changes, surface embrittlement and changes in gloss, and by applying Raman microscopy and atomic force microscopy. Our results clearly show the influence of the additives used and also a very good correlation between microscopic investigations and macroscopically observable degradation, such as formation of cracks and loss of gloss. Among the test methods, confocal Raman microscopy displays several important advantages. It is a rapid, non-destructive and spatially resolving analytical method which can be used to optimise the relevant material parameters and their resistance to aging as an aid to their application in solar energy systems.

Our work is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

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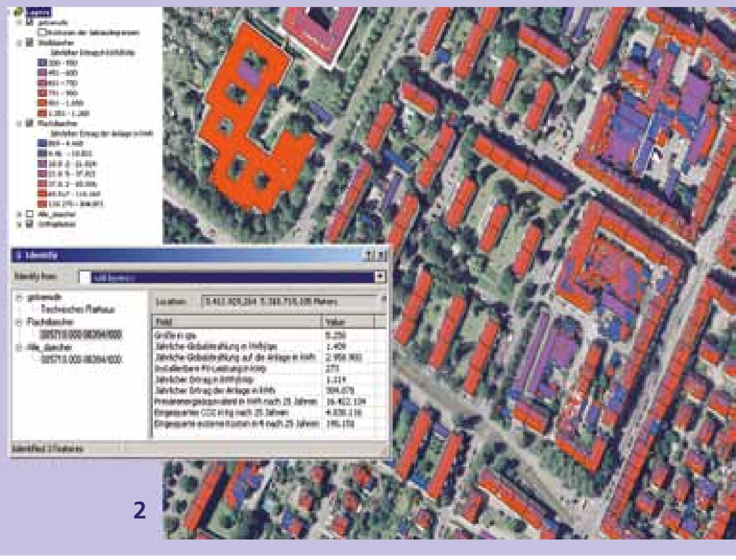


2

PV POTENTIAL AS A LOCATION FEATURE

As part of an undergraduate thesis, a method was developed and applied to determine the theoretical, technical and economic potential to use solar energy within a selected geographical region. The required data were collated in a Geographical Information System (GIS). In addition, estimates were made of the primary energy which could be substituted, the potential to avoid CO_2 emission and the external costs which could be avoided if the economically viable PV potential were realised.

1 *False-colour representation in the GIS plan of the annual solar irradiation on roof areas in kWh m^{-2}.*

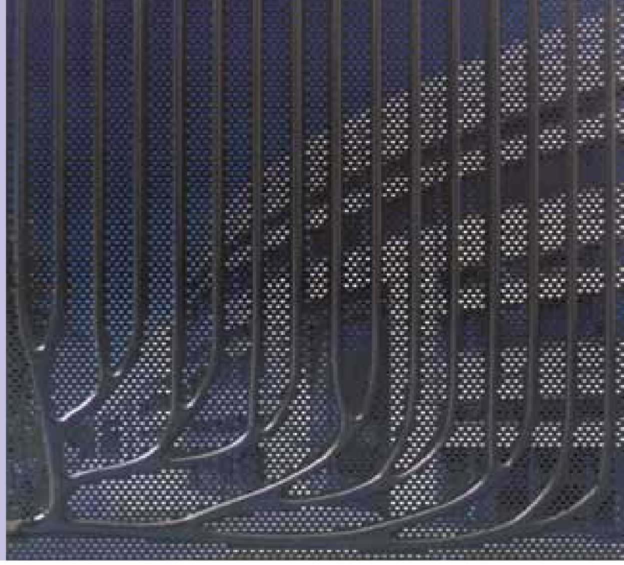
2 *Output of information on a selected individual roof area in the GIS plan.*

Claudio Ferrara, **Michael Köhl**, Karl-Anders Weiß,
Pascal Zimmer, Hans-Martin Henning

A procedure was applied as part of an undergraduate thesis at Fraunhofer ISE to calculate the solar energy potential of roof areas in a defined geographical region and to determine whether individual roofs were suitable for the installation of solar energy systems. Due to the combination of different data sources – an automated real estate map ("automatisierte Liegenschaftskarte" – ALK), Light Detection and Ranging (LIDAR), meteorological data – and presentation of the results in a Geographical Information System, the user can seek information on specific, individual buildings and generate new results. This approach presents a major advantage in comparison to other potential assessment methods, as it offers better spatial resolution and allows all groups involved to act on their own initiative. The procedure was initially applied to a 3 x 3 km^2 test area within the city of Freiburg im Breisgau, Germany. The theoretical, technical and economic potential for photovoltaics was calculated for this test area. In addition, correlated quantities were estimated, such as the primary energy which could be substituted, the potential to avoid CO_2 emission and the external costs which could be avoided if the economically viable PV potential were realised.

The developed procedure can also be transferred to other regions. In this way, an important framework has been created to determine the potential for solar energy application in any desired region within a short period of time. Only the input data for the roof area extraction and the radiation simulation need to be adapted. For example, a solar "registry" covering a whole state or even the whole country could be prepared and suitable areas to install thermal and photovoltaic solar energy systems could be identified. Actors of all kinds – including public offices and institutions, landlords, housing bodies, energy utilities and private owners – would profit from the results and could both achieve financial gains by appropriate investment and also contribute to wider application of solar energy.

1



2

ACTIVE SOLAR FAÇADES

High solar utilisation factors can only be achieved for many large buildings when the façade is also used to gain energy, as the roof area is relatively small. In particular, simultaneous usage of the façade and the roof is needed to gain sufficient energy for large zero-energy or plus-energy buildings. Fraunhofer ISE has achieved first successful results in developing multi-functional façade components which can be installed in the transparent part of the building envelope.

Francesco Frontini, Michael Hermann, **Tilmann Kuhn**, Christoph Maurer, Helen Rose Wilson, Hans-Martin Henning

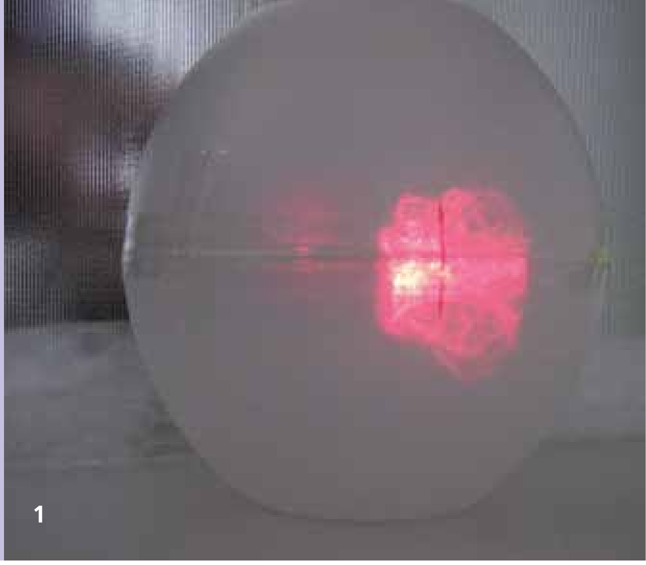
Around 40 % of the CO_2 emissions within the EU are due to buildings. On the other hand, zero-energy buildings with a neutral primary energy and CO_2 balance are already possible today and will be required by law for new buildings from 2018, when the resolution of the European Parliament of April 2009 is implemented. Larger buildings with a relatively small roof area and a large façade area can function as zero-energy or even plus-energy buildings only if the façade is also used to gain energy.

1 Prototype for a new generation of angle-selective, transparent BIPV elements with improved efficiency for vertical installation, very good protection against glare and overheating and improved visual contact to the outside world. The prototype demonstrates only the optical functionality; the structure has not yet been manufactured with active PV elements.

2 Visualisation of a new, transparent thermal façade collector, which can be integrated into a glazing unit. The holes in the absorber have an angle-selective transmittance to improve the efficiency for vertical installation, to achieve good protection against glare and overheating and to allow visual contact with the surroundings.

Within an EU-funded project, Fraunhofer ISE is developing components and systems with the goal of using not only opaque but also transparent façade areas to gain energy (www.cost-effective-renewables.eu). This is particularly important in fully glazed buildings, in which the new components are intended primarily for use in the spandrel region. There, they also simultaneously help to reduce cooling loads in summer.

The prototypes demonstrate that effective g values of < 10 % can be achieved to prevent overheating in summer, while good visual contact to the surroundings is retained. The BIPV glazing unit in Fig. 1 shows that very good protection against glare can also be achieved, with DGP values of < 0.30 (DGP = Daylight Glare Probability). This type of glazing is also very well suited for use in large, fully glazed rooms in airports or similar non-residential buildings.



1

Structure	Tnh,sol according to EN410 (patterned glass samples)		(polished glass samples)
	average (15 instruments)	σ (15 instruments)	measured
flat	0.905	0.001	0.904
slightly rippled	0.901	0.004	0.903
small inverted pyramids	0.888	0.012	0.905

2

TRANSMITTANCE OF LOW-IRON, PATTERNED SOLAR GLASS

The transmittance of the cover glass directly affects the efficiency value of a flat-plate collector. Nevertheless, often significant errors are made in measuring the transmittance of frequently used, patterned "solar glass", if commercially available integrating spheres are used. This was demonstrated by analysing the results of a measurement round robin, which was co-ordinated by Fraunhofer ISE and conducted by members of Technical Committee 10 of the "International Commission on Glass" (ICG-TC10).

Angelika Helde, Johannes Hanek, Tilmann Kuhn,
Helen Rose Wilson, Hans-Martin Henning

1 *Laser beam after transmission through patterned solar glass into a translucent sphere. The patterned surface, with a structure consisting of small inverted pyramids, faced the sphere. The spatially inhomogeneous distribution of the transmitted beam is obvious and causes errors in the measurement of such patterned glass with commercially available integrating spheres.*

2 *Average and standard deviation (σ) values measured for the normal-hemispherical solar transmittance (Tnh,sol) for three types of patterned "solar glass". The Tnh,sol values for polished samples from the same glass charges represent the upper limit for the solar transmittance of this type of glass.*

So-called "solar" patterned glass is often used for collector covers, referring to patterned glass with a low content of iron oxide. Both the surface structure and also the low absorptance of the glass make it more difficult to measure optically than is the case for conventional flat glass with the usual iron oxide content.

In the round robin of ICG-TC10, 15 measurement laboratories provided spectral measurement results for five different types of glass. The structures ranged from flat (as a control) to inverted pyramids of different dimensions. Some results of the comparison are summarised in Fig. 2. Whereas the results show excellent agreement for the flat control samples, even the results for the "flattest" structure ("slightly rippled") show that specifying the transmittance with more than two significant figures is not justified. In general, the rougher the structure, the greater is the deviation among the measurement results.

Transmittance and reflectance values were also measured for flat samples which were prepared by grinding and polishing the patterned glass. We derived theoretical limits for the transmittance by combining these measurement results with geometrical optics. Comparison with the measurement results revealed that as the structures become increasingly "rough", not only the standard deviation but also the deviation of the average value from the theoretically correct value increases. Caution is thus needed, for example if collector yield predictions are based on such measurement values.

In commercial integrating spheres, different reflectance values for different zones within the sphere present a common cause for error in the measurement of patterned solar glass. The design and the wall material used in the integrating spheres developed at Fraunhofer ISE reduce this error significantly.

CYCLING STABILITY OF SORPTION MATERIALS

Thermally driven adsorption heat pumps or chillers in the low power range have recently become commercially available. With a view to successful market penetration, operation must be guaranteed for typical system lifetimes. To this purpose, we carry out stability investigations on sorption materials and composites that are relevant to the intended applications, using specially developed aging test equipment.

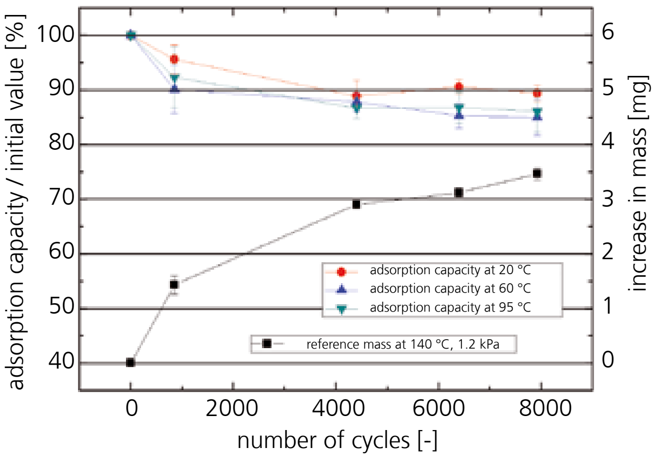
Stefan K. Henninger, Gunther Munz, Sebastian Müller, Karl-Friedrich Ratzsch, Peter Schossig, Peter Villain, Hans-Martin Henning

Experience gained in previous developments indicated that intensive lifetime analysis of the materials intended for use in adsorption heat pumps and chillers is necessary. Taking account of the entire development chain, we are thus investigating the stability of materials ranging from synthesis products in powder form, through granulates, to composite samples consisting of metallic matrix structures and sorptive coatings. The samples are subjected to thermal and mechanical stress which is derived from application conditions in a real sorption chiller or heat pump in routine operation. This is characterised by a sequence of adsorption and desorption phases, resulting in rapid temperature changes for the material in a pure water vapour atmosphere.

This "hydrothermal" stress is imitated by heating up to 140 °C and cooling down to 20 °C in the corresponding atmosphere, both in a thermogravimetric balance to determine changes in mass and also in special cycling equipment. While the thermal stress is applied, the samples are continuously characterised with respect to their sorption behaviour with precise thermoanalytical instruments and visible changes are documented. The results of these investigations provide valuable information on the suitability of sorption materials, matrices, additives and differing production procedures for concrete application areas.

The work is supported by the Ministry for the Environment of the State of Baden-Württemberg.

1 *Sample holder with a composite sample in the opened vacuum chamber of the test rig for long-term cycling. The equipment provides room for three composite samples in isolated units which can be controlled independently of each other. (Very short heating and cooling times of 90 s each, a temperature range of 20 – 140 °C and very large numbers of cycles – 10,000 within three weeks – are possible.)*



2 *Reduction in the adsorption capacity of a composite sample due to the hydrothermal stress. A decrease of 10 % can already be seen after 500 cycles. The capacity continues to decrease, whereby stabilisation after app. 4000 cycles can be detected. At the same time, the reference mass is observed to increase. Both effects can be explained by partial destruction of the structure, accompanied by simultaneous accumulation of degradation products.*

MONITORING OF SOLAR COOLING SYSTEMS

Detailed knowledge of the operation of installed systems is essential for system optimisation and to determine the savings in primary energy resulting from solar-thermally driven air-conditioning and cooling units. Fraunhofer ISE is involved in several detailed monitoring projects which encompass both the demonstration of commercially available technology and the testing of innovative technology for solar cooling. Two examples are presented in the following article.

Jochen Döll, **Tomas Núñez**, Jakub W. Wewiór, Edo Wiemken, Peter Schossig, Hans-Martin Henning

Solar-thermally assisted air-conditioning for the FESTO Technology Centre

The app. 26,000 m² office area of the FESTO Technology Centre in Esslingen-Berkheim has been air-conditioned since 2001 by adsorption cooling technology with a rated cooling power of 1.05 MW. The chillers are driven by waste heat from the production facility, by gas-fired boilers and, since 2008, with solar-thermal heat. A 1218 m² (aperture area) array of evacuated tubular collectors was installed to this purpose. Only water is used as the collector fluid. It is obvious that only a small portion of the heating demand of this large building can be met by solar heat from an array with these dimensions. By modifying the operation management of the gas-fired boilers in 2009, the joint contribution of solar heat and waste heat to the total heat demand for the adsorption chillers was increased to a maximum of 80 % during the summer months. The project ran within the "Solarthermie 2000plus" Programme that was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

1 *Solar cooling system for a Tunisian winery.*

Solar Process Cooling Power for Agricultural Products in the Southern Mediterranean Region

In 2008, a solar cooling system (Fig. 1) was installed in a Tunisian winery as part of the EU-funded "MEDISCO" project (www.medisco.org). The system consists of a linearly concentrating Fresnel collector with 88 m² of primary reflectors and a 12 kW water-ammonia absorption chiller with an integrated dry heat rejection unit. Driving temperatures of 120 °C and more are needed in order to produce cold brine with temperatures of about 0 °C under high outdoor temperature conditions combined with dry heat rejection. The initial measurement data for the current pilot system have demonstrated the feasibility of this concept and show that the Fresnel collector reaches the required temperatures and that cooling power at 0 °C can be provided by a solar energy system.

1

PHASE-CHANGE SLURRIES

Phase Change Slurries (PCS) are heat-storage fluids with an elevated heat capacity over a certain temperature range due to their content of dispersed phase-change materials (PCM). Use of these slurries is an option wherever heat or cooling power must be stored within limited temperature ranges. The storage capacity of the PCS varies between about 50 and 100 kJ kg^{-1}, depending on the PCM concentration.

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

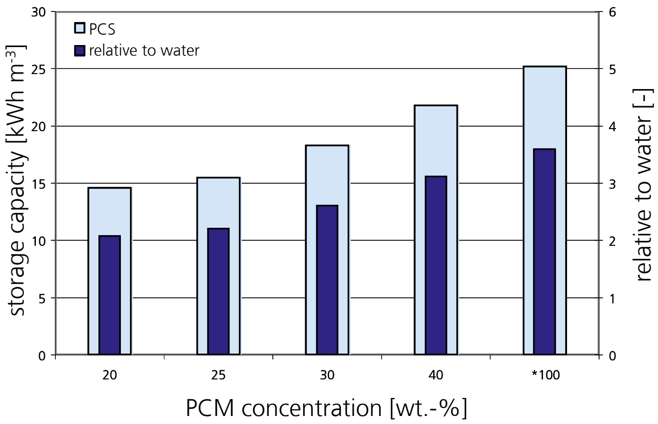
PCS consist of two main components: A liquid and PCM particles, which are dispersed in the liquid. Water is the most commonly used liquid but other liquids such as heat-transfer oils are also possible. To date, mainly paraffin has been used as the PCM. As paraffin is hydrophobic, it can be directly emulsified in water with the aid of an emulsifying agent. In another approach, the PCM is initially micro-encapsulated and then suspended in the liquid. Micro-encapsulated PCM can be suspended in many different liquids.

A high PCM concentration in a PCS results in a high heat capacity. As the viscosity also increases strongly with the concentration, this sets limits on the concentration. Our investigations demonstrated that emulsions have lower viscosity for the same PCM concentration than micro-encapsulated PCS. However, the micro-encapsulated PCS have achieved greater long-term stability to date. With them, we have achieved stability over more than 20,000 cycles.

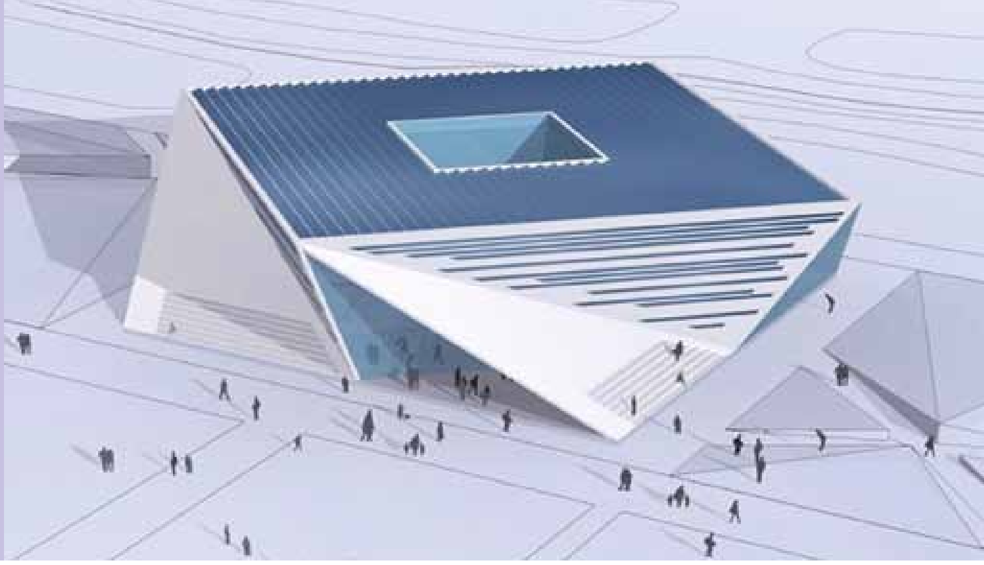
Use of PCS is particularly interesting for applications which tolerate only a small temperature difference, such as cooling applications. Here, the storage capacity can often be increased only by reducing the temperature or enlarging the storage tanks. This results in poor efficiency of the chillers or large, voluminous storage tanks. Particularly when cooling power is generated to cool buildings, there is no point in obtaining low storage temperatures, as the cooling temperatures can be similar to the intended room temperatures (e.g. 20 °C).

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

1 Phase Change Slurries consist of a phase change material and a liquid. The mixture is a dispersion which remains fluid, regardless of the physical state of the phase change material. The viscosity depends on the concentration of the dispersed PCM.



2 The advantage of a PCS compared to water as a heat-transfer fluid depends strongly on the concentration of PCM in the liquid. It should be noted that the viscosity of the PCS also increases strongly with increasing PCM concentration.



CONCEPTION OF A ZERO-ENERGY BUILDING FOR THE CITY OF SEOUL

Fraunhofer ISE co-operated with a planning consortium to design a zero-energy building for the city of Seoul. In the planning phase, we reduced the energy demand of the exhibition and office building, with a usable area of 3000 m², to the extent that the annual demand can be met on average purely regeneratively by photovoltaics. Building construction will start in 2010.

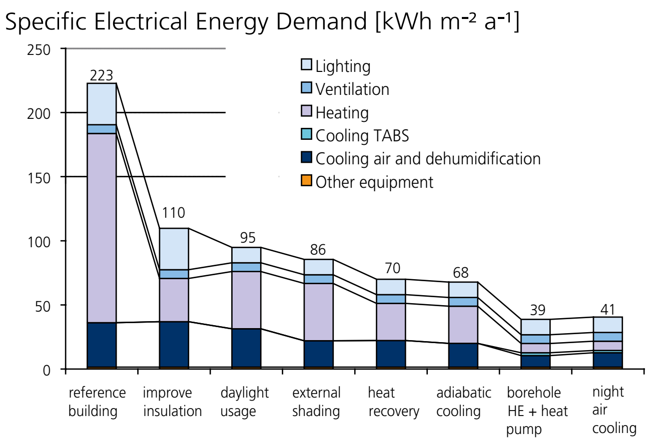
Sebastian Herkel, **Jan Wienold**, Hans-Martin Henning

The city of Seoul commissioned Fraunhofer ISE to design and plan a net zero-energy building. An approximately 3000 m² building was planned in co-operation with the "GAP" architectural office, the "solidar Planungswerkstatt" project manager, the "solares bauen" HVAC planner and BAHO, the Korean building developer. About a third of the floor area serves as an exhibition area and a further third as an edutainment zone. The remaining third is available to companies from the renewable energy sector for use as offices.

In the first planning step, the energy demand of the building was reduced to a minimum. The prevailing climate in Seoul forced the planning team to minimise both heat losses in winter and the energy demand for cooling and, even more importantly, for dehumidification in summer. The building envelope was designed such that thermal bridges were kept to a minimum. The glazed fraction was tuned to provide good daylighting but simultaneously prevent excessive solar gains in summer.

Heat is supplied from a borehole heat pump and is distributed via a heating and cooling system integrated into the floor. The high air humidity in summer, accompanied by low direct solar radiation values, presents a problem for a regenerative cooling energy supply, as solar-thermally driven sorptive cooling processes are out of the question. Instead, the inlet air to the building is conventionally dehumidified by a highly efficient turbo-compressor cooling system and the air flow rate is reduced to the hygienically required minimum. The required further cooling energy is provided by the boreholes and distributed via the floor-integrated system. A 200 kWp PV system will be installed to supply the electricity for building operation from regenerative energy sources.

1 *3D visualisation of the net zero-energy building in Seoul that was conceived by Fraunhofer ISE together with its project partners.*



2 *Influence of various investigated measures to reduce the building electricity demand relative to the current standard reference building in Korea. Each additional measure (from left to right) was considered additively. The total result is a reduction by more than 80 % (relative to the standard reference) of the remaining electricity demand to operate the building. (TABS: thermally activated building system)*

© Herbert Stolz, Regensburg

HOUSE OF THE FUTURE – THE ACTIVE SOLAR "SONNENKRAFT" HOUSE IN REGENSBURG

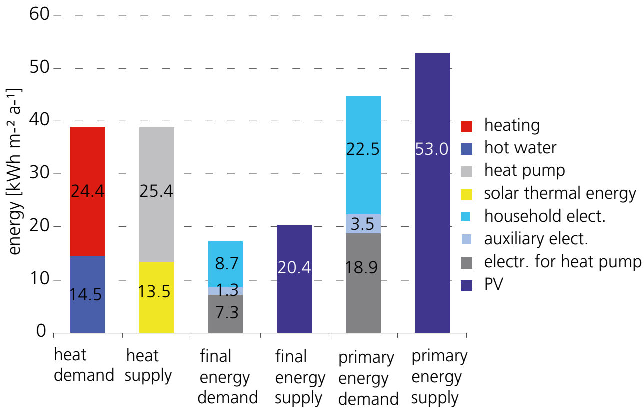
Energy supply concepts for new buildings are focussing increasingly on the net zero-energy approach. Based on a strongly reduced total energy demand for a building, the goal is to achieve an annual balance between the demand and supply of primary energy from regenerative sources. Solar thermal energy is used in different ways in the project presented here by combining it with a heat pump, providing an interesting approach to increase the efficiency of the total system.

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

A concept for a free-standing, net zero-energy house was prepared for the "Sonnenkraft" company in co-operation with "fabi architekten", Regensburg and the University of Applied Sciences in Regensburg. The objective was to reduce the building energy consumption for operation and usage to the point that an overall annual balance can be achieved with the supply of solar energy.

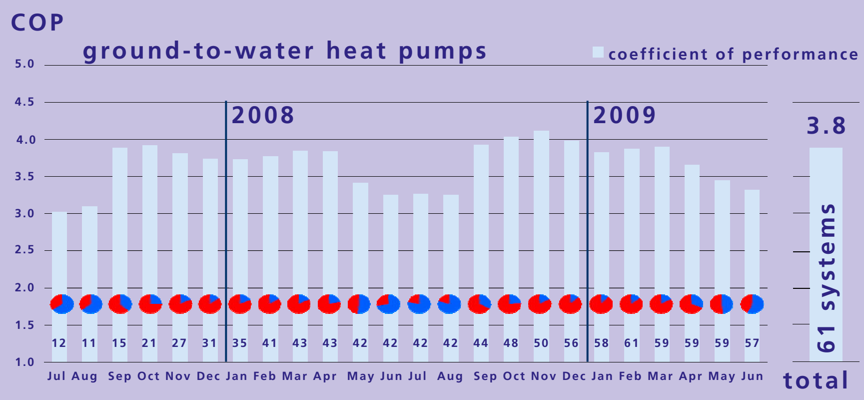
To this purpose, a building design was developed which architecturally integrates the components for comprehensive use of solar energy by passive (windows) and active means (photovoltaics and solar-thermal collectors). In addition to the building design, a heat pump system was conceived in which both the outdoor air and solar thermal energy can be used as the heat sources, depending on the temperature level and availability.

1 Southern aspect of the building with integrated thermal collectors in the façade (80 ° tilt) and PV modules as the roofing (27 ° tilt).



2 Balance of energy demand and supply for heat, final energy and primary energy. The building features a positive annual balance for the final and primary energy due to the solar yield from the photovoltaic system. The goal to achieve a net zero energy building is more than met.

If the collector output temperatures are too low to recharge the tank, the heated water is used to raise the temperature level of the source/evaporator side of the heat pump, increasing its efficiency. System and building simulations predict that this will increase the annual coefficient of performance for this specific case from 2.9 for a heat pump operating purely with outdoor air to 3.4. Combined with 50 m² of photovoltaics and 35 m² of thermal solar collectors, the building is calculated to be a "plus-energy" house with a positive primary energy balance on an annual basis. Performance data will be measured over the next two years, allowing detailed analysis and quality control of the concept.



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MONITORING OF HEAT PUMPS – FIELD TEST OF 180 SYSTEMS

In Germany, sales in 2008 increased by 27 % for ground-to-water heat pumps and by 33 % for air-to-water heat pumps, compared to the figures for 2007. This development documents the acceptance of these supply systems both in new buildings and in the existing building stock. Analysis of 180 heat pumps in a field test with respect to energy, ecology and economy revealed that planning and installation must be adapted to the demand, if primary energy and CO_2 emissions are to be saved.

Holger Dittmer, Danny Günther, Lukasz Kaczmarek, Thomas Kramer, **Marek Miara**, **Christel Russ**, Hans-Martin Henning

Since 2007, we have been evaluating the efficiency of heat pumps with respect to energy, ecology and economy for a total of 180 systems in two field tests, "Heat Pump Efficiency" for new free-standing and semi-detached houses, and "Heat Pumps in the Building Stock" for existing buildings. The measurement data are recorded every minute. The data document the heat flow quantities on both the heat source and heat sink sides, including the inlet and outlet temperatures and the flow rates. By recording data on the electricity consumption for the compressor, the brine pump or fan, the electric auxiliary heating and the charging pumps in the heating circuit, it is possible to determine an accurate energy balance for the complete supply system.

89 % of the investigated new houses are equipped with floor heating; the average output temperature for all heating systems is 38 °C. Among the investigated buildings in the existing building stock, 71 % are equipped with water-heated radiators and the average output temperature is around 52 °C. The average annual coefficients of performance for all systems in 2008 were

- for new houses: 3.8 (ground-to-water) and 3.0 (air-to-water)
- for existing buildings: 3.3 (ground-to-water) and 2.6 (air-to-water)

To assess the system efficiency in greater detail, further system parameters such as the heat source, the heat sink and the hydraulic system configuration were investigated more closely. As an example, analysis of the annual coefficients of performance for different system concepts in new houses revealed:

- direct use of heat via floor heating and separate domestic hot water tank: 3.88
- heating supply via a buffer tank and separate domestic hot water tank: 3.8
- combined tank for heating and domestic hot water: 3.51

Our results provide a basis for manufacturers as they optimise their systems to improve their overall efficiency. The project was partly funded by the German Federal Ministry of Economics and Technology (BMWi).

1 *Ground-to-water heat pumps in new buildings ("Heat Pump Efficiency" Project): The average monthly coefficients of performance, and the proportion of heat generated for space heating and domestic hot water (DHW), are shown for all ground-to-water heat pumps from 2007 to 2009. The coefficient of performance is lower in summer than in winter, as the DHW share is dominant, with its higher inlet temperatures. The pie graphs show the monthly distribution of generated heat for space heating (red) and DHW (blue).*

2 *Example of an installed heat pump system. The following components are visible in the background: The installed heat meters for the measurement data acquisition and the electric junction box with the electric meters to record the electricity consumption of the compressor, the brine pump or the fan, and the heating-circuit pumps.*

COST-EFFECTIVE ERROR DETECTION IN BUILDING OPERATION

Eliminating errors and optimising building operation has the potential to save 5 – 30 % energy. The measures taken here require little or no investment. We are developing methods and tools to identify this potential quickly and inexpensively. Initial results indicate that the methods can be applied economically.

Sebastian Burhenne, Dirk Jacob, **Christian Neumann**, Nicolas Réhault, Sebastian Zehnle, Hans-Martin Henning

The potential to save energy in the existing building stock is enormous. Simply by setting the control parameters correctly, generally 5 – 30 % of the end energy demand can be saved and the figure can be higher in individual cases. Usually it is a matter of taking simple measures such as adapting programmed schedules to the system operation, setting heating and cooling curves correctly or adapting air flow rates.

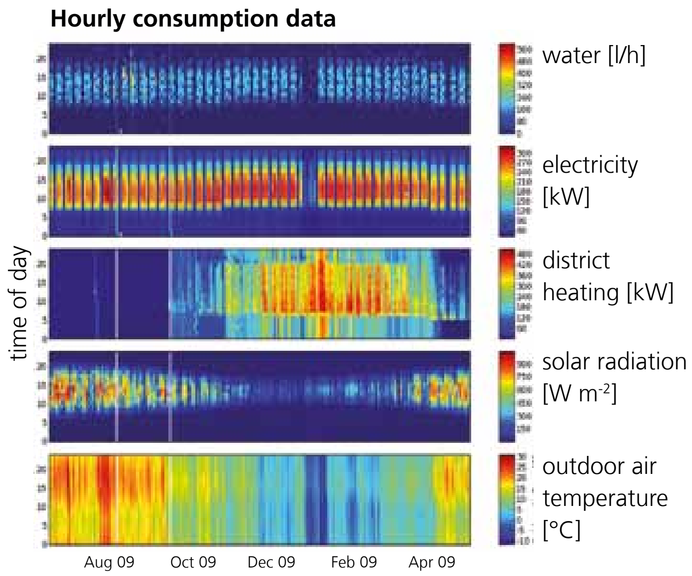
In the "Building EQ" and "ModBen" projects, we are developing procedures and tools to identify this potential as quickly and inexpensively as possible, and then to exploit the potential permanently. We are currently testing these procedures in more than 15 demonstration buildings. (www.buildingeq.eu and www.modben.org)

The starting point for our analyses is acquisition of a well-defined set of measurement data, which is recorded in each building. We have developed a tool which offers the following functions, based on this data set: Data storage and processing, intelligent visualisation of the data, model-based analyses and automatic detection of outliers to identify cases of unusual consumption.

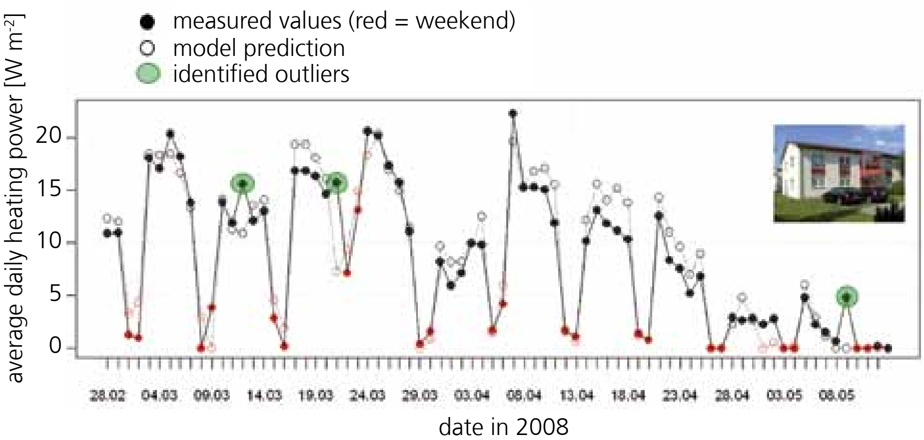
On the one hand, typical errors in building operation can be recognised with the help of these functions, and simple optimisation measures can be applied on the basis of this information. On the other hand, the automatic detection of outliers helps to ensure that operation continues to be optimal on a permanent basis after it has been initially optimised.

We were able to achieve savings between 10 and 40 % in the demonstration buildings. The investments needed to install the data acquisition equipment and carry out the initial analysis were statistically amortised within 0.5 to 3 years.

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

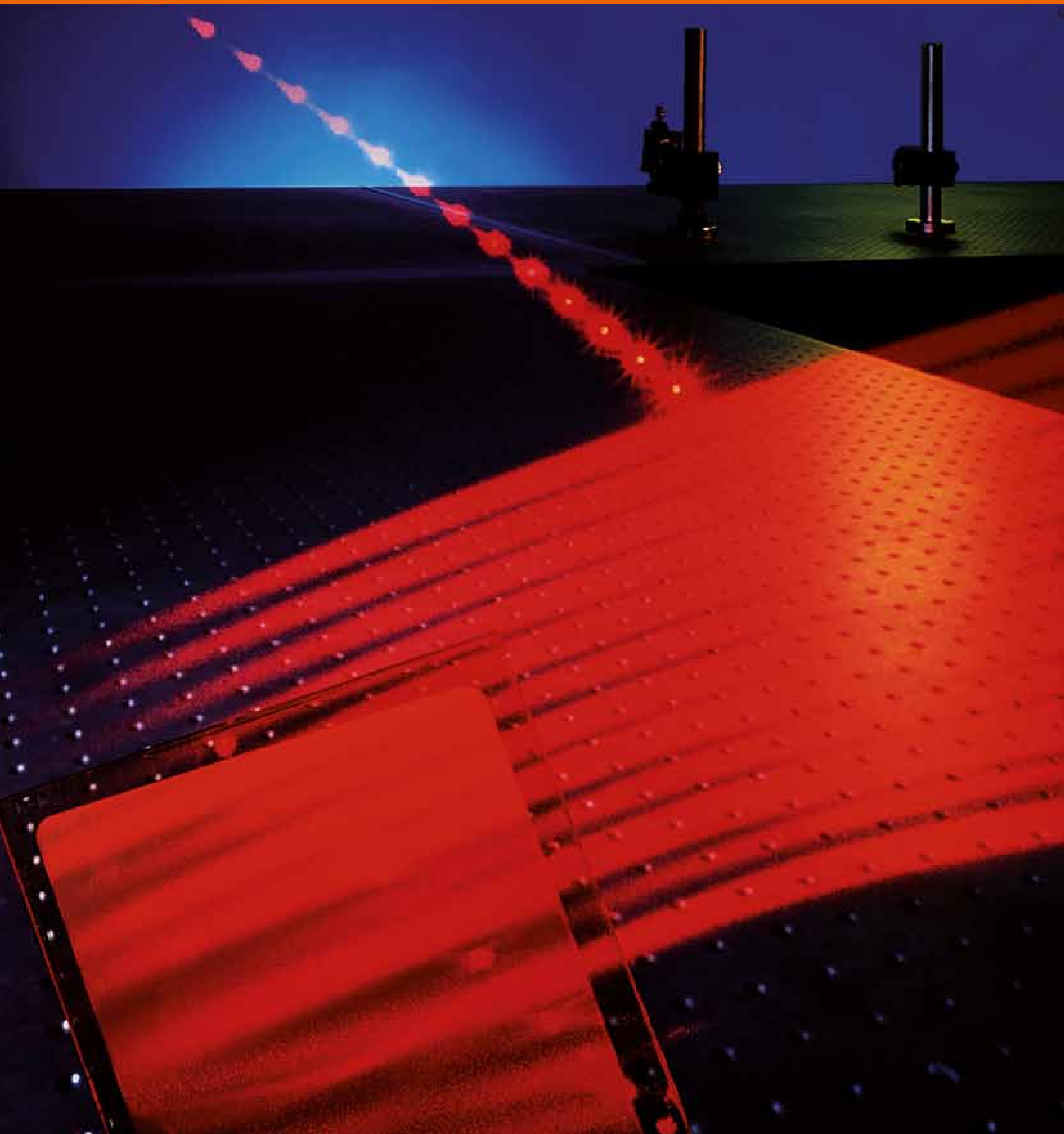


1 *Intelligent visualisation: Each individual plot shows the variation of a measured quantity with time as a coloured pattern. Days with similar operation display a similar range of colours, so that typical patterns result. These can be interpreted simply and quickly by trained professionals.*



2 *Automatic identification of outliers: The daily energy and water consumption can be monitored automatically with the aid of special regression models. Initially, the model must learn how the building reacts ("calibration"). After the learning phase, the model can be used to check the performance. The figure shows a comparison between the model prediction and measured values for the heating energy consumption per m² floor area of a small office building.*

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.

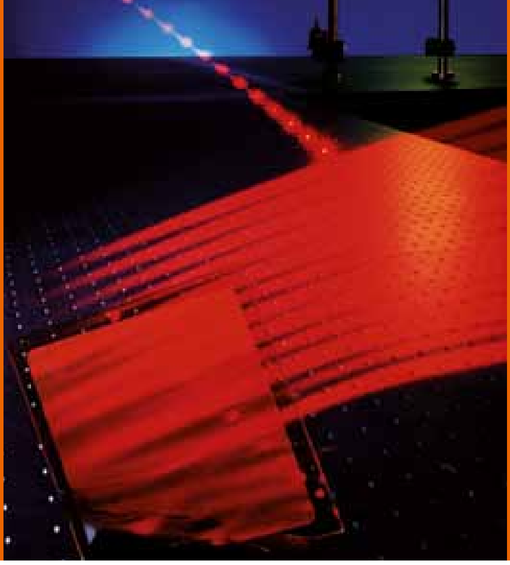
Effective control of the light and solar energy fluxes through the façade is becoming increasingly important for energy-efficient buildings with large glazed areas. Switchable coatings on window panes allow the window transmittance to be changed over a wide range. As non-mechanical solar-shading systems, they offer advantages with regard to viewing quality and vulnerability to wind damage, for example. Our gasochromic glazing, in which the absorption can be adjusted over a wide range, has already 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. 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, luminance measurements with imaging methods, fringe reflectometry, special measurement facilities for concentrating optics

Micro-structured surfaces with optical and other functions are developed in the interference-lithography laboratory of Fraunhofer ISE. Application fields include both solar-shading systems, which reflect undesired direct solar radiation and yet still transmit diffuse daylight, and also photonic gratings and light-trapping structures to increase the efficiency of organic and silicon solar cells. Microstructures provide functions such as anti-reflective effects, light redirection, defined scattering of light, suppressing of pixel effects, polarisation, outward light coupling and inward coupling of daylight, also for displays or advertising panels. They thereby improve the contrast quality and resolution, and improve the system efficiency.

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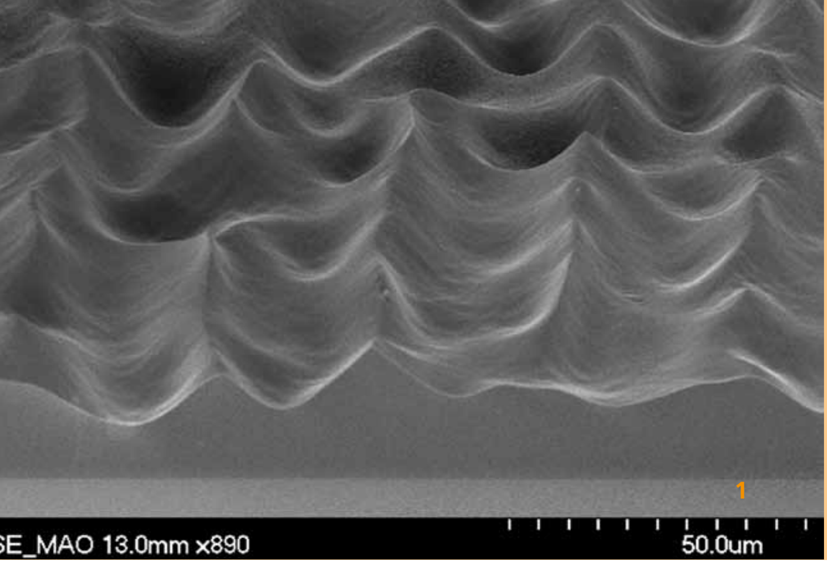
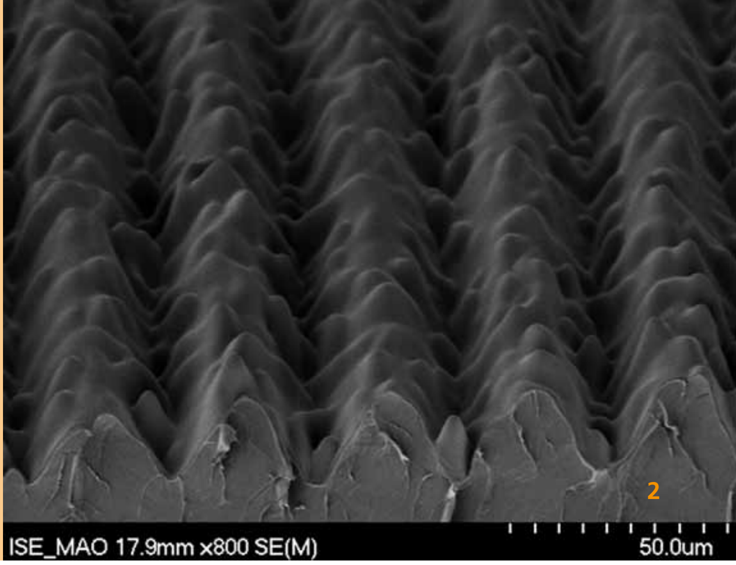




CUSTOMISED OPTICAL DIFFUSERS OVER LARGE AREAS

Optical diffusers are required in many applications. Diffusing plates which scatter light with a complex, well-defined angular distribution are of particular interest. With newly developed interference-lithographic processes, we are able to create diffusers with a customised scattering characteristic over large areas.

Benedikt Bläsi, Volkmar Boerner*, Volker Kübler, Jörg Mick*, Michael Nitsche, Andreas J. Wolf, Werner Platzer

* Holotools GmbH

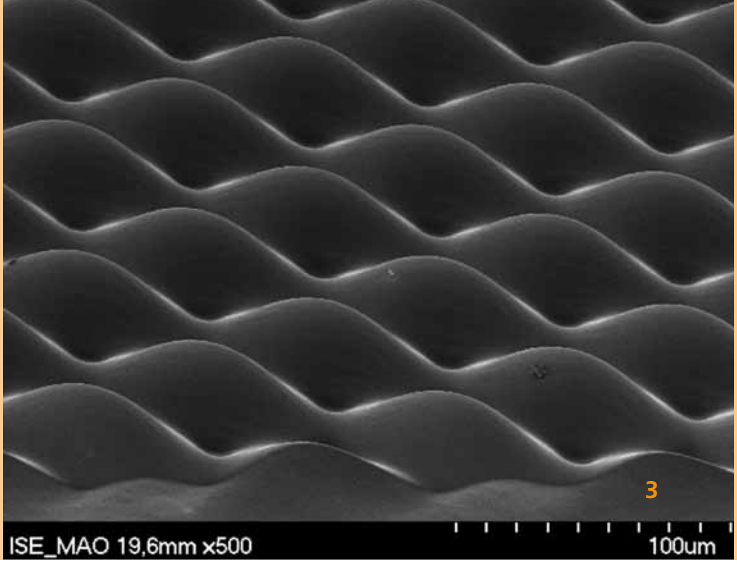
1 *Scanning electron micrograph of the surface of an anisotropically scattering diffuser. The master is shown here. The interface with the glass substrate is visible below the structured photoresist layer.*

2 *Scanning electron micrograph of a diffuser surface with a "bat-wing" characteristic. The microstructure was transferred to the transparent polymer, polymethyl methacrylate (PMMA), by hot embossing.*

Optical diffusers or scattering plates are needed in many products, e.g. displays, luminaires, photovoltaic systems or glazing. Depending on the application, a well-defined scattering effect in transmission or reflection is demanded. In addition, such diffusers are required over large areas.

Interference lithography is a technology which allows surface structures to be produced homogeneously on the micrometre and nanometre scale over areas of more than 1 m^2 with greatest precision. With this process, we are able to create periodic and stochastic profiles and thus produce the masters for surface diffusers with a customised scattering characteristic. These masters are then used to produce embossing tools, which can then be applied to manufacture large-area diffusing plates by micro-replication processes such as hot embossing, UV replication or nano-imprint lithography. We developed diffuser structures for large-area projection displays within the EU-funded "OSIRIS" project. Depending on the final application (front or rear projection, 2D or 3D reproduction), very diverse specifications had to be met, for example, scattering in transmission or reflection, or differing degrees of anisotropy in the scattering characteristic. The development of a structure started with wave-optical simulations, which we used to model the scattering behaviour of different surface profiles and design ideal target structures. Subsequently, we adapted the interference-lithography process to the relevant scattering characteristic by optimising the choice of photoresist, the substrate coating, exposure and development.

Three types of diffuser structures will be described as examples in the following paragraphs:



Anisotropically scattering projection screen for transmitting and reflecting applications

The challenge associated with this optical element, which is needed for 2D and 3D displays, was to achieve large scattering angles in one direction and small scattering angles in the other. In particular, this anisotropy must be very pronounced for 3D applications. We implemented this functionality with an anisotropic stochastic structure, which we produced on substrates with an area of 120 x 70 cm^2 (Fig. 1).

"Bat-wing" diffuser

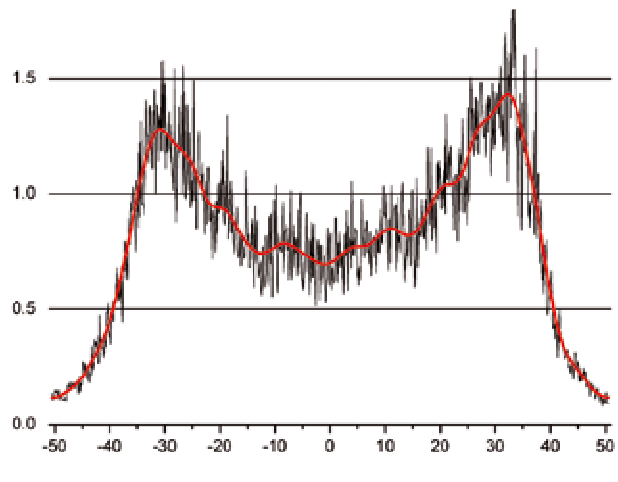
This scattering plate features particularly strong redirection of the incident light toward large scattering angles. It is primarily of interest for back-lighting of displays or in luminaires, as the light emitted e.g. by fluorescent tubes can be distributed very favourably. We achieved the "bat-wing" functionality with a combination of several exposures with periodic and stochastic interference patterns (Figures 2 and 4).

Asymmetrical micro-lens arrays

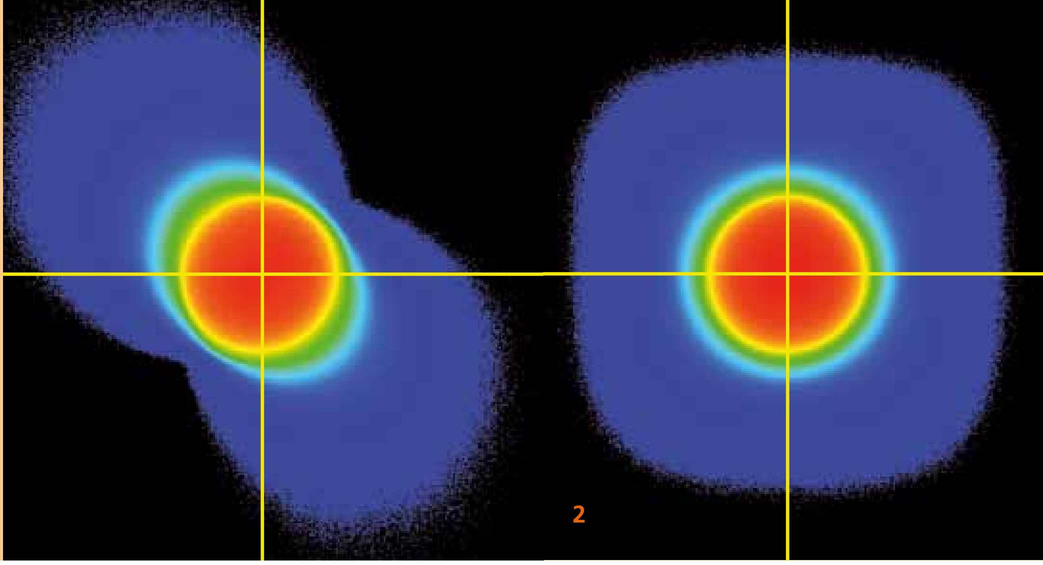
To create structures with a very precisely defined, anisotropic scattering characteristic, we have developed a process to produce asymmetrical micro-lenses. By establishing interference between three waves, we were able to generate elongated lenslets. Their exact geometrical configuration can be adjusted by a combination of the exposure geometry and polarisation (Fig. 3).

The work was funded by the EU within the "OSIRIS" integrated project.

3 *Scanning electron micrograph of an asymmetrical micro-lens array, which was generated in photoresist by interference between three waves, and then replicated in silicone.*



4 *Scattering characteristic of a "bat-wing" diffuser in transmission (length scale in relative units). The maxima at angles exceeding 30 ° are clearly evident. The measurement was made with a laser, which resulted in significant noise in the black curve (speckle effect). In addition, the smoothed scattering characteristic is shown in red.*



CHARACTERISATION OF FRESNEL LENSES FOR CONCENTRATOR PHOTOVOLTAICS

In photovoltaics with flat modules, sunlight is collected by large-area semiconductors and converted into electricity. Concentrator photovoltaics (CPV) reduces costs by covering large areas with cost-effective optical components, which then focus the light onto significantly smaller solar cells. We characterise the Fresnel lenses which are used for this purpose in our measurement facility. This allows design and manufacturing processes to be optimised and quality to be controlled.

Thorsten Hornung, Martin Neubauer*, **Peter Nitz**, Werner Platzer

* Concentrix Solar GmbH

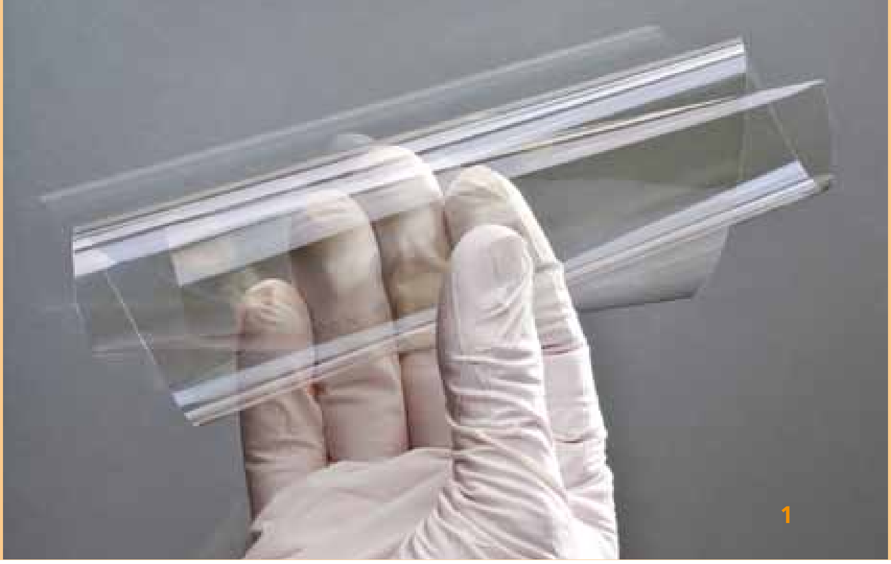
1 *The measurement facility to characterise Fresnel lenses consists of a mobile holder for lens arrays, a light source above and a camera below. The light source generates white or monochromatic light, which is available as a parallel beam or with divergence similar to the sun, as required. The camera can be moved into the focal spot of the lens and records the intensity distribution there.*

2 *We carried out four separate measurements of different sectors of a square Fresnel lens with an edge length of 60 mm. The light intensity that was determined during the measurement of one sector is shown in a colour-coded representation on the left. Subsequently, we calculated the image shown on the right of the focus of the complete Fresnel lens from the four individual measurements. The relative deviation in the optical efficiency to a direct measurement of the complete lens is less than 1 %.*

In concentrator photovoltaics, Fresnel lenses are often used to concentrate the sunlight (see also article on p. 75). These lenses must be subjected to accurate optical characterisation, both to optimise the manufacturing process and optical design, and for ongoing quality control during industrial production. Several years ago, we established a measurement facility in our laboratory, with which individual lenses and entire panels with lens arrays can be thoroughly characterised optically. A monochromatic or white light source illuminates the lenses with light that is essentially parallel or features a similar divergence to sunlight. In the focal volume of the lenses, a CCD camera (charge-coupled device) detects the spatial distribution of the irradiation with high linearity, which we analyse to determine the focussing quality with very high accuracy.

Larger formats for the lens arrays necessitated the construction of an extended and improved version (Fig. 1). Square Fresnel lenses with an edge length of up to 60 mm, round lenses with diameters of more than 80 mm and lens arrays up to 450 x 850 mm^2 can be measured directly. Individual zones of still larger lenses are measured separately. The mechanical components of the test rig operate so accurately that the individually measured zones can be combined to form a complete image (Fig. 2). In this way, we are currently able to characterise lenses with an edge length of up to 120 mm and focal lengths exceeding 60 mm.

Furthermore, we can investigate particularly interesting zones of the lenses in even greater detail and regulate the lens temperature, so that temperature-dependent effects can be studied. We compare the measurement results with our optical or thermo-mechanical models of the lenses, thereby gaining insight into the causes of the effects observed.



TRANSPARENT ELECTRODES BASED ON THIN SILVER FILMS

Thin silver films embedded in oxide layers feature high electrical conductivity and high light transmittance. They are already used as low-emissivity coatings in insulating glazing units, but can also be applied as electrodes for solar cells or light-emitting diodes if the oxide layers are suitably adapted. As they are very thin (app. 10 nm), they are inexpensive and can be deposited well onto flexible polymer substrates. For certain applications, adaptation of the work function is particularly important.

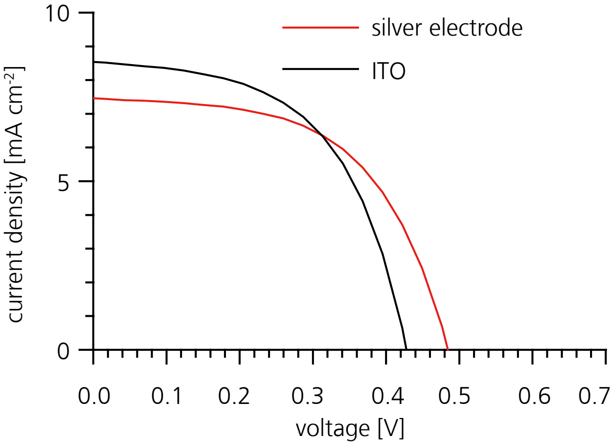
Andreas Georg, Leonard Kraus, Thomas Kroyer, Hans-Frieder Schleiermacher, Tobias Schosser, Werner Platzer

Silver-based electrodes consist of thin silver films (film thickness of app. 10 nm), which are embedded between oxide layers (thickness of app. 50 nm). Such thin-film stacks have long been used as low-emissivity coatings for architectural glazing. Here, light transmittance values of 89 % and an electric sheet resistance of 4 Ω are typically achieved. Conventional transparent electrodes based on indium tin oxide (ITO) are relatively expensive. Silver electrodes present an inexpensive alternative.

In particular, the oxide layers have to be adapted for this application. For some systems such as organic solar cells or light-emitting diodes, the work function of the material must be adapted. By varying the metal in the metal oxide, it was possible to vary the work function by 1 eV. Variation of the oxygen content resulted in a change of app. 0.3 eV. The demands on the electrical conductivity of the metal oxide are very moderate, particularly in comparison to conventional transparent conductive oxides (TCO's).

Tuning of the film thicknesses allows greater advantage to be taken of interference effects than would be possible with the significantly thicker TCO films. In this way, the absorption in a solar cell can be increased, for example. Specifically in organic solar cells, acidic media can be used. In this case, if suitable embedding oxides are chosen, the silver electrode is more durable than aluminium-doped zinc oxide or ITO, which are commonly used as transparent electrodes.

1 *Transparent silver electrode on a polyester film.*



2 *Current-voltage characteristic curves for organic solar cells with electrodes of ITO or silver.*

Silver electrodes can readily be deposited onto flexible polymer substrates, which is not easily possible for conventional TCO's (Fig. 1). Figure 2 shows the current-voltage characteristic curve for an organic solar cell with a silver electrode and an ITO layer, as is commonly used as the electrode. The expensive ITO can be replaced by a silver electrode without decreasing the efficiency value.

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.
In the past, component development and applications for thermal use of solar energy were investigated within different business units at Fraunhofer ISE. The common features of the diverse system approaches were not addressed jointly. Fraunhofer ISE has now decided to emphasise the common aspects of these various applications and systems in order to strengthen synergy between the participating working groups and the corresponding types of technology. To this purpose, a business unit addressing "Solar Thermal Technology" has been created.

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 more than 400 °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 must permanently withstand much higher temperatures (up to 450 °C). 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.

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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 systems on an industrial scale. Their economic feasibility can be clearly improved by heat and power (and cooling power) cogeneration and simpler operating conditions.

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
- 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

FRESDEMO test collector at the Plataforma Solar de Almería in Spain. This collector was used to demonstrate the technical feasibility and practical operation of Fresnel technology for the first time in relevant dimensions. Fraunhofer ISE optimised the collector concept in accordance with the goal of minimising the specific energy generation costs. A good number of freely selectable parameters, such as the number of reflector rows and the form of the secondary reflectors, had to be taken into account. The industrial partner, Solar Power Group/MAN Ferrostal Power Industry, was responsible for the construction. Fraunhofer ISE coated the receiver tube and the secondary reflectors, i.e. the key components.

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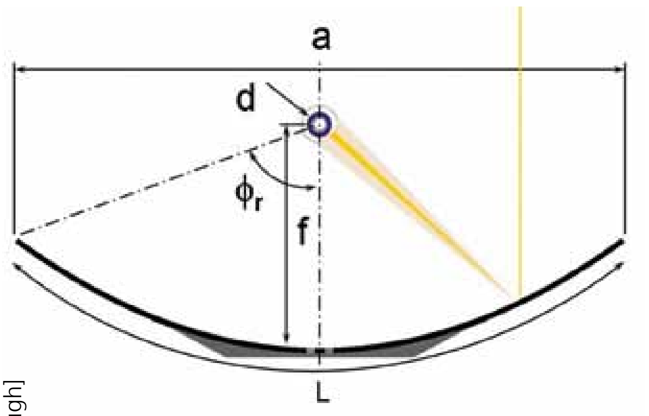
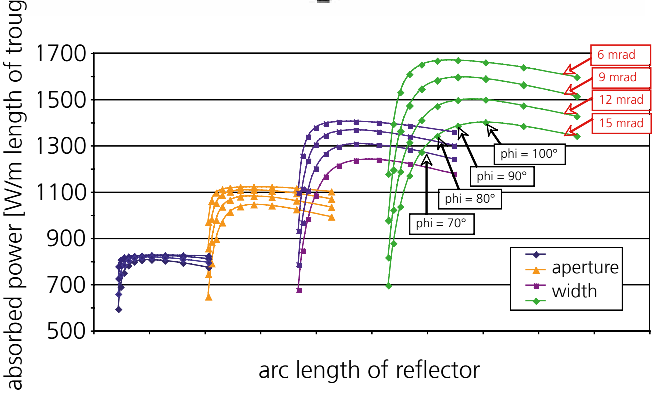
DESIGN OPTIMISATION OF PARABOLIC TROUGH COLLECTORS

Small parabolic trough collectors are particularly well suited to generating process heat at temperatures between 180 °C and 300 °C. We are supporting industrial partners in the development of their collectors by systematically investigating the effects of reflector material, geometrical configuration and optical accuracy. We apply ray-tracing for optical modelling. We characterise relevant reflector materials in the laboratory and use the detailed results in our design studies.

Anna Heimsath, Stefan Hess, Paolo di Lauro, Peter Nitz, Thomas Schmidt, Hans-Martin Henning, Werner Platzer

Parabolic trough collectors with aperture widths of 1 – 2 m use direct solar radiation to generate process heat. The direct radiation is concentrated by parabolic reflectors onto an absorber (Fig. 1). Concentrating collectors are particularly well suited to generate industrial process heat in the temperature range > 180 °C and for co-generation of process heat and electricity.





Many parameters and materials must be determined in the development of a new collector. At Fraunhofer ISE, we apply ray-tracing to model the various design options. Geometrical dimensions, component properties and imaging errors are integrated into the models. The result of the optical simulation is the angle-dependent optical efficiency, which can then be used to calculate annual yields for specific locations and geometrical configurations of the collector array.

In order to predict the performance with the greatest possible accuracy, individual collectors and their materials must first be characterised. Relevant specific optical properties include the angle-dependent direct reflectance, the beam divergence caused by the reflector surface and the exact form of the parabolic trough. Knowledge of these data allows us to model the collector properties as realistically as possible.

Within the "dCSP" project, a systematic, theoretical study was conducted on the influence of the collector geometry and accuracy of the reflectors on the optical yield of a small, parabolic-trough collector. The work was commissioned by the Alcan Speciality Sheet and Alcan Innovation Cells companies.

1 *Design of a small parabolic trough for process heat. The direct solar radiation is reflected by a parabolic reflector onto the absorber pipe. Innumerable combinations of the aperture width (a) and focal length (f), the boundary angle (ϕr) and absorber diameter (d) are possible. Cost optimisation finally provides the basis for deciding on the most favourable design for implementation.*

2 *Influence of the aperture width, boundary angle (phi) and reflector error (as beam dilation in mrad) on the absorbed power (per trough metre), plotted against the amount of material (arc length) needed for the reflector sheet. The calculation is based on assumptions of direct irradiation of 1000 Wm^{-2}, no thermal losses and variation of the boundary angle between 30 ° and 120 °. The different colours indicate increasing aperture widths (from blue to green).*

DESIGN OPTIMISATION OF SOLAR THERMAL POWER PLANTS

As with all technical systems, different parameters have to be optimally adapted to each other during the design of solar thermal power plants. We have developed a novel approach, which integrates the various technical and economic component models and a powerful multi-parameter optimisation process such that different design variables, from the collector array to the power plant process, can be optimised simultaneously.

Torsten Gutjahr, **Gabriel Morin**, Sanmati Naik, Pascal Richter, Werner Platzer

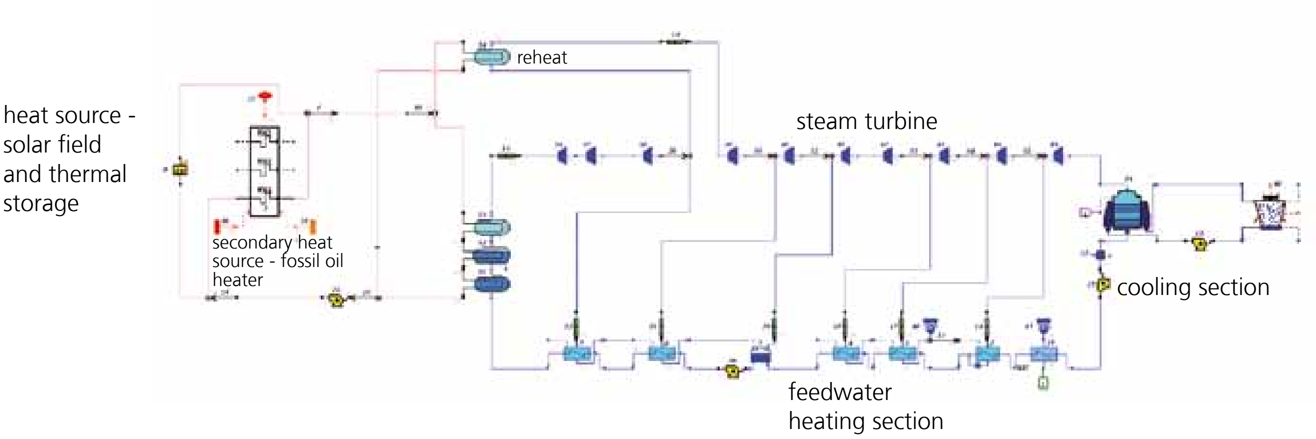
Over the past years, we have followed an approach which aims to fully exploit the optimisation potential in designing concentrating solar collectors by simultaneously taking all technical and economic factors into account in an integrated program package. After we had successfully applied this methodology to the product development of concentrating solar collectors, we have now extended the methodology to entire power plants, specifically including the conventional power plant components.

Usually, when a solar thermal power plant is designed today, the solar array, power plant process and other components are dimensioned sequentially, and then the configuration is evaluated economically. With this sequential approach, it is very time-consuming to optimise the dimensioning of a solar thermal power plant according to economic criteria.

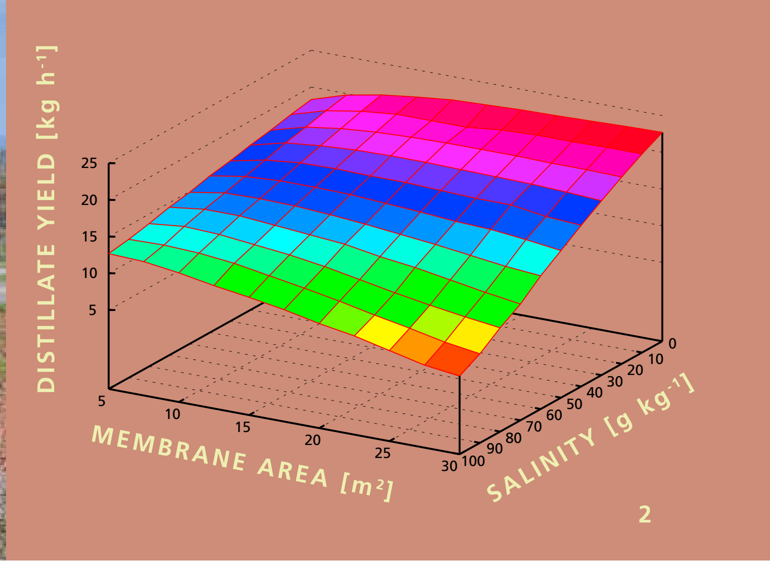
We have thus linked the technical and economic simulation programs for the sub-systems via interfaces to an efficient optimisation procedure, so that parameters can be optimised which are relevant to the specific case. Following an approach similar to biological evolution, the optimisation procedure constantly creates new, improved parameter configurations, so-called individuals.

Starting from a power plant design based on the Spanish 50 MW Andasol I power plant with parabolic trough concentrators, we optimised the following parameters simultaneously with respect to the electricity production costs as an application example: Solar array dimensions, distance between parallel rows of collectors, capacity of the thermal storage unit, operating temperature and the process components including condenser, cooling tower, feed-water pre-heating section and reheating section.

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



1 *The new feature of the integrated OPTISIM simulation package is that the conventional power plant components are also modelled in detail and are simultaneously optimised during the design process. To do so, we use the Thermoflex program, which contains a cost estimation module in addition to the energy simulation.*



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.

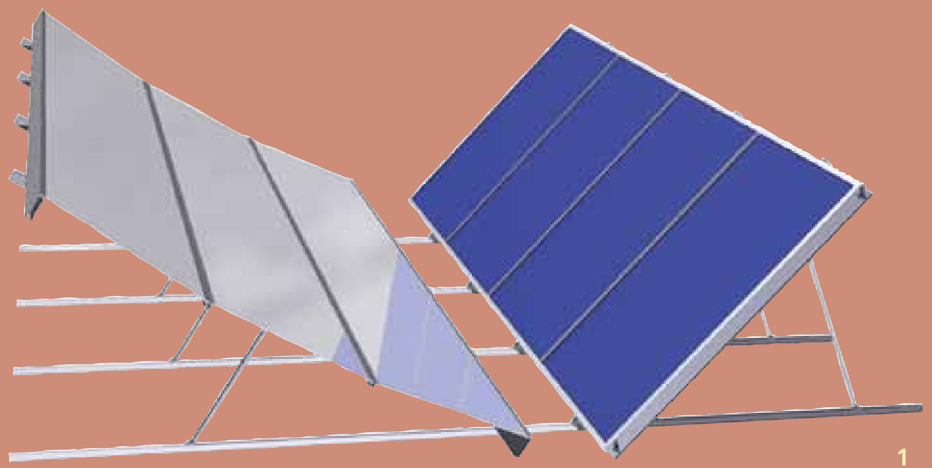
Florian Groß, Mario Hillebrand, **Joachim Koschikowski**, Christian Schirmer, Hamdi Timoumi, Marcel Wieghaus, Daniel Winter, Hans-Martin Henning

1 *Two identical, solar-driven membrane distillation systems for comparative investigations. The collector area is 7 m² in each case. The typical system capacity is between 90 and 150 l per day.*

2 *Simulation results to analyse the distillate yield as a function of membrane area and salinity of the untreated water. These results are valid for certain fixed operating parameters (inlet temperature, inlet water flow rate). On this basis, the module configuration can be adapted to specific operating conditions.*

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. We focus on energy-autonomous systems, which are used for decentralised water purification. In order to carry out detailed investigations of the complete system, we have constructed two identical systems on our test field (Fig. 1). Here, different operating modes, the effect of different components or different MD module configurations can be investigated in parallel under identical environmental conditions.

We also use these operating results to validate our simulation models, which accurately reproduce the physical transport process in the MD module and in the complete system. The simulation result illustrated in Fig. 2 demonstrates how important it is to match the module configuration to the system operation. The graph shows that the yield of distillate from water with a low salt concentration increases as the membrane area increases. However, when strongly saline water is treated, enlarging the membrane area may significantly reduce the yield under certain circumstances. Within various projects, we are currently setting up several MD systems (0.15 – 5 m³/day) driven by solar or waste heat in Italy, Tunisia, Namibia and the Canary Islands, in co-operation with our partners from research and industry.



LOW-TEMPERATURE PROCESS HEAT WITH THE REFLEC CONCEPT

About a fifth of the European final energy consumption is used as industrial process heat – a significant fraction of this can be provided at temperatures lower than 150 °C. For several years, we have been working in this temperature range, including the "RefleC" project, in which we are supporting the company, Wagner & Co. Solartechnik, in the development of a double-glazed flat-plate collector with external reflectors to supply process heat.

Stefan Heß, Paolo di Lauro, Axel Oliva, Hans-Martin Henning

To determine the optimal reflector geometry, we have systematically varied the acceptance half-angle, reflectance, reflector form and other collector parameters with the help of ray-tracing simulations. For each variant, the optical efficiency and the angular dependence of the incidence angle modifier (IAM) were calculated for direct radiation. We were able to validate our optical simulations with outdoor measurements of three test samples. Previously, several collector components had been measured optically at Fraunhofer ISE. We also tested the resistance of various reflector materials to hail impact with ice spheres as projectiles.

We have theoretically investigated the thermal and optical losses for various materials as the second collector cover and gap distances to the outer cover, and validated the models with measurements.

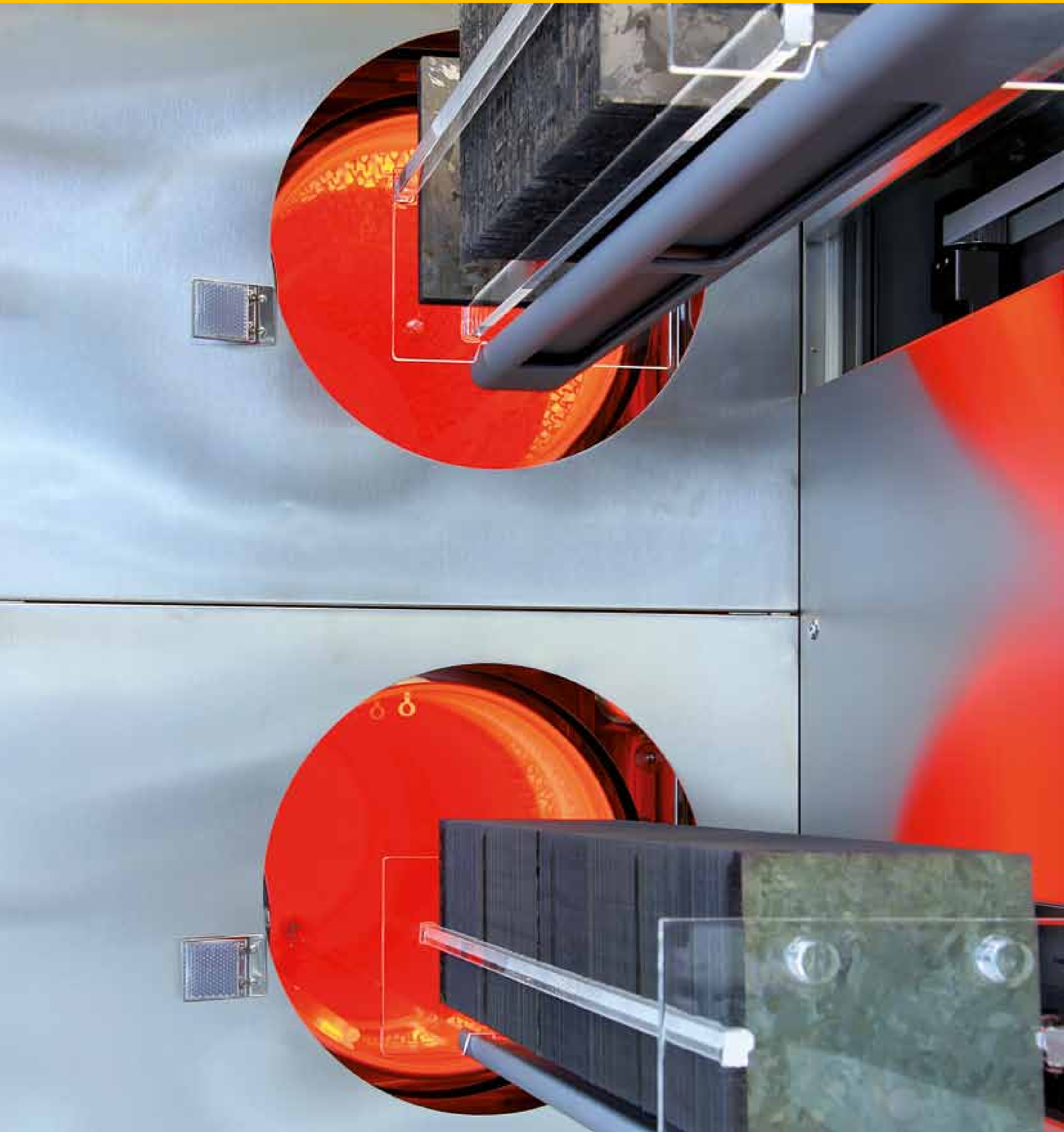
To calculate the collector yields, we have developed a new module for the TRNSYS simulation program, in which the diffuse radiation is distributed anisotropically over the sky hemisphere. With the IAM for direct radiation from the ray-tracing simulations, we are thus able to determine the radiation accepted by the collector correctly. In designing the collector, it is also possible to adapt the maximum collector performance to the seasonal load profile. When calculated with meteorological data for Würzburg, the gross collector yield for the variant shown in Fig. 1 is 50.7 % higher than that of a double-glazed flat-plate collector without a reflector for a constant inlet temperature of 80 °C, and becomes 130 % higher for an inlet temperature of 120 °C. With the isotropic distribution of diffuse radiation over the hemisphere, which is assumed on a standard basis in the simulation, the yield at 120 °C is underestimated by app. 20 %.

The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the "Solarthermie 2000plus" Programme.

1 *Reflectors and flat-plate collectors mounted on a flat roof form long rows, with the substructure for the reflectors supporting the row of collectors in front of it. The thermal losses were reduced significantly by use of a second cover and reflectors. The IAM for direct radiation reaches values up to 1.5.*

2 *Measurement of the efficiency characteristic for the collector variant illustrated in Fig. 1 at Fraunhofer ISE. We were able to measure the efficiency characteristic for operating temperatures up to more than 180 °C in our test rig for process-heat collectors. The measured values to determine the IAM were corrected such that we could derive the IAM for direct radiation alone.*

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, Spain and other European countries: The globally installed peak power capacity has already increased to more than 15 GW.

Appreciably more than 80 % of the rated power was 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.

In our clean-room laboratory, we are setting standards in advancing the development of high-efficiency solar cell concepts and processes. 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. The excellent processing infrastructure in the clean-room laboratory, with a floor area of 500 m^2, has allowed us to set several international records for efficiency. In processing technology, we also concentrate on effective surface passivation methods, novel metallisation and doping procedures and innovative nano-structuring technology.

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 photoluminescence method to analyse silicon material and cells.

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.

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. 67), 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.

Loading process for the tubular diffusion furnace, which is equipped with highly efficient in-line measurement technology, at the Photovoltaic Technology Evaluation Centre PV-TEC of Fraunhofer ISE. Up to 200 silicon wafers are doped or oxidised under controlled conditions at temperatures of 800 to 1000 °C. PV-TEC has been accelerating the technology transfer from the laboratory to the industry since 2006. In PV-TEC at Fraunhofer ISE, manufacturers of solar cells, wafers, modules and production equipment can analyse and further develop processes, materials and systems, without having to interrupt production on their own production lines. The flexible configuration of technological equipment at PV-TEC allows alternatives to be offered for each processing step.

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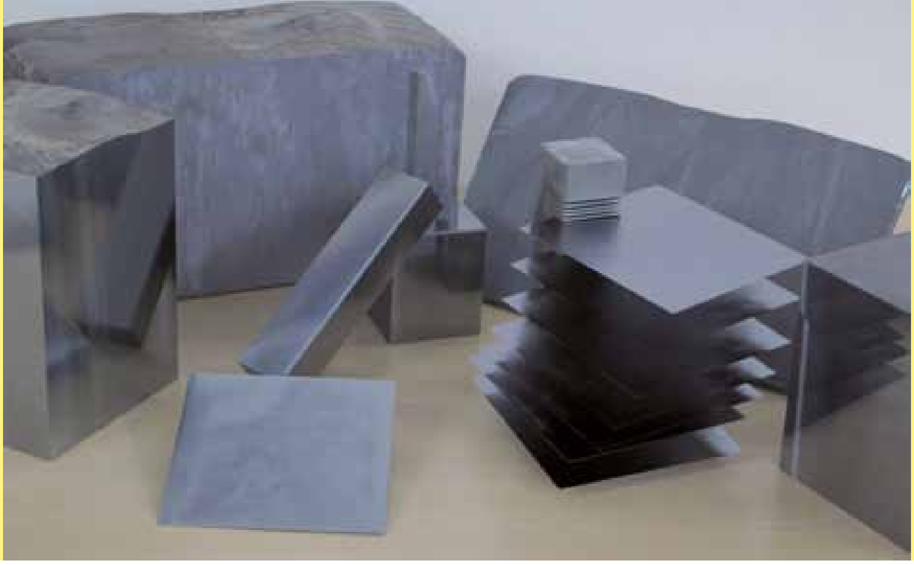

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CRYSTALLISATION AND ANALYSIS OF NEW FEEDSTOCK MATERIALS

In the Silicon Material Technology and Evaluation Center SIMTEC, we have developed modified crystallisation processes for research on new feedstock materials. Our crystallisation features different crucible dimensions and our own crucible coatings. In combination with a complete block-processing and sawing line, including purification, we have the flexibility to investigate new materials and their behaviour during solar cell processing, as well as quantifying their effects on cell properties.

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

1 Silicon blocks are processed flexibly into wafers and other sample forms, depending on the requirements. The photo shows a selection of multicrystalline columns of different dimensions produced on the sawing line, wafers of various thicknesses and samples with specially customised forms.

With completion of the crystallisation and sawing area in SIMTEC at Fraunhofer ISE, we have greatly expanded the possibilities for research at the beginning of the value-creation chain for crystalline silicon solar cells. Work in the crystallisation sector focussed on a near-industrial Vertical Gradient Freeze (VGF) system for solidifying multicrystalline silicon blocks. We are conducting research on new feedstock materials and crucible systems, and investigate fundamental problems both on a small and an industrial scale. To this purpose, we have established a process to produce small research blocks with masses of 10 to 20 kg silicon, in addition to the crystallisation of 80 kg silicon for medium-sized blocks and 250 kg for the largest blocks. This facility enables us to crystallise new feedstock materials also in small quantities, and subsequently to investigate the efficiency of the resulting solar cells at Fraunhofer ISE. We use not only industrial quartz crucibles and crucible coatings, but also our own coatings, in order to optimise their interaction with only moderately purified metallurgical silicon, for example. For further processing of the blocks, a complete sawing line including a purification bench is operational on site, and is used to produce columns, wafers and special sample forms for our research projects and external clients.

A further focus of our research on silicon wafers is to investigate the chemical and mechanical properties particularly of wafers made of favourably priced silicon. If the wafers are to be used as substrates for epitaxially grown solar cells, they must be very stable mechanically under thermal loads. Initial investigations indicate that there are great variations in the performance of different feedstock materials. This provides important information on the conditions required during further processing.

The work was financed within the framework of the "Silicon Beacon" research project by the Fraunhofer-Gesellschaft.

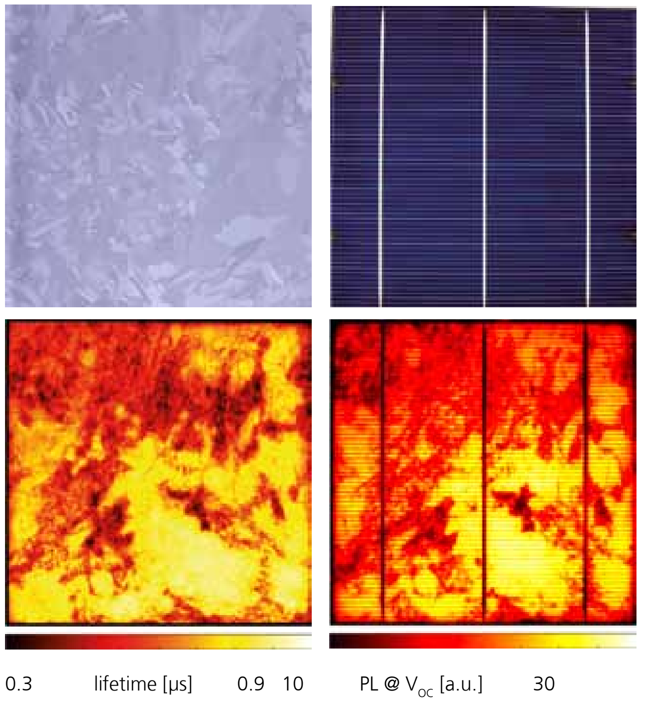
LUMINESCENCE-BASED QUALITY CONTROL OF WAFERS

Controlling the quality of silicon wafers before they are processed poses a great challenge to the PV industry. Conventional methods do not provide adequate information for the solar cell performance to be predicted from the electrical properties of the feedstock material. Based on photoluminescence measurements, we have developed a procedure with which we can detect material defects reliably and correlate these with the expected effect on solar cell efficiency.

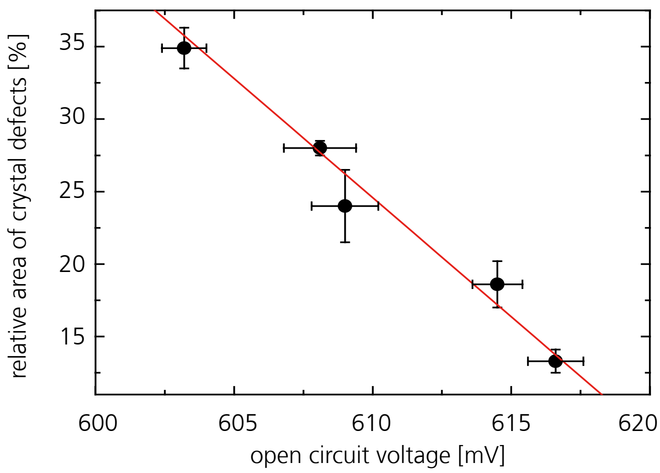
Matthias Demant, Gernot Emanuel, Markus Glatthaar, Jonas Haunschild, Wolfram Kwapil, **Stefan Rein**, Meinrad Spitz, Ralf Preu

Camera-based photoluminescence (PL) measurement technology presents a promising new measurement method for quality control in PV production, as it makes electrically relevant defects visible with a high spatial resolution in measurement times of < 1 s. In addition, it can be applied at almost all stages of processing, from the untreated "as-cut" wafer through to the final solar cell. We have developed the PL method further, particularly with regard to its in-line applicability, and have tested initial quality control procedures in our research production line at PV-TEC.

One of the most important electrical parameters of a wafer is the charge carrier lifetime. Unfortunately, this parameter changes strongly during the course of the solar cell process, such that the lifetime which can be measured for the as-cut wafer allows only a very rough classification of the material. With the PL method, we have now succeeded in establishing a correlation between the as-cut wafer and the final solar cell by analysing and interpreting the measurable image contrasts. Figure 1 shows the PL images of an as-cut wafer and the completely processed solar cell made from the same wafer. It is clearly evident that the structures in the brightness contrast are retained. These recombination-active structures can be attributed to crystal growth faults during the crystallisation process. By applying appropriate image-processing algorithms, we can determine the proportional area occupied by the crystal defects. As Fig. 2 shows, this quantity, which is determined for the as-cut wafers, correlates excellently with the open circuit voltage of the final solar cell. The proportional area of crystal defects thus presents a suitable measure to evaluate the electrical quality of the untreated wafer, which allows us to predict the voltage of the final solar cell as part of the incoming wafer control procedure.



1 *Photos (upper half) and PL images (lower half) of a wafer at two stages of processing: Initial as-cut state (left) and after the complete solar cell production process (right). Both display identical structures in the brightness contrast, which indicate the electrical quality of the material.*



2 *The proportional area of crystal defects in the as-cut wafer (Fig. 1, left) can be determined with a simple image-processing algorithm before solar cell production starts. The correlation with the open circuit voltage of the final solar cell (Fig. 1, right) demonstrates that we can use this parameter for detailed quality control of the feedstock material.*

This work was supported by the Fraunhofer-Gesellschaft and within the "QUASSIM" project by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

DISTRIBUTION OF METALLIC IMPURITIES IN SILICON: SPATIALLY RESOLVED DETECTION AND SIMULATION

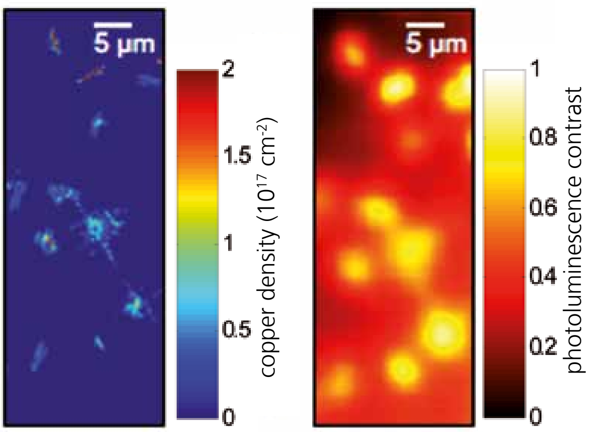
Apart from the concentration, the spatial distribution of metallic impurities is particularly decisive for the performance of multicrystalline solar cells. We investigate metal precipitates with highly sensitive synchrotron measurements. In parallel, dissolved iron impurities can be quantitatively determined with the aid of lifetime measurements. Our fundamental understanding of precipitate behaviour is deepened by multi-dimensional numerical simulation.

Paul Gundel, Holger Habenicht, Wolfram Kwapil, Jonas Schön, **Martin Schubert**, Wilhelm Warta, Stefan Glunz

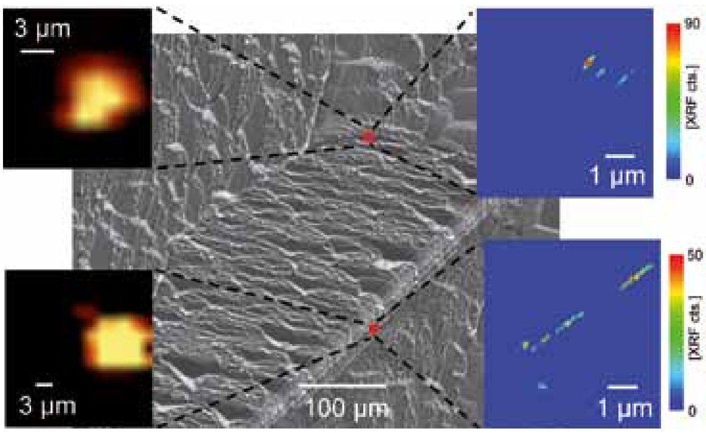
In contrast to high-purity monocrystalline silicon, the shorter charge carrier lifetime limits the performance of solar cells made of less expensive multicrystalline silicon. In particular, metallic impurities form point defects and precipitates which promote recombination and limit the efficiency. In addition to the total impurity concentration, the spatial distribution of the metal atoms plays a decisive role in determining the achievable solar cell efficiency which can be achieved.

In order to adapt solar cell processes optimally to the multicrystalline feedstock material, it is essential to measure the metal distribution. Redistribution of metals during high-temperature steps and purification by gettering processes can be understood and optimised with the help of this information.

Metal precipitates can be detected via X-ray fluorescence measurements with synchrotron sources. In addition to obtaining the finely resolved spatial distribution, the chemical composition can be determined from the fluorescence spectrum. In the case of iron, the most significant impurity, the concentration distribution of the dissolved impurity can be determined quantitatively and with high spatial resolution in parallel. A specific property of interstitial iron atoms is exploited to achieve this: In the dark, the iron atoms bind to boron atoms, which are present in a high concentration due to the p-type doping. Under illumination, the atom pairs dissociate again. As the recombination parameters for the two configurations differ, the recombination lifetime changes under illumination. With the help of high-resolution lifetime meas-



1 *Detection of recombination activity by photoluminescence spec troscopy and comparison with X-ray fluorescence spectroscopy to detect iron precipitates at the ESRF synchrotron. The iron precipitates were prepared with the help of a large-area dislocation system consisting of two extremely flat monocrystalline silicon wafers, which were chemically covalently bonded, and to which iron impurities were deliberately added. Comparison of the recombination activity and the iron distribution allows quantitative microscopic correlation.*

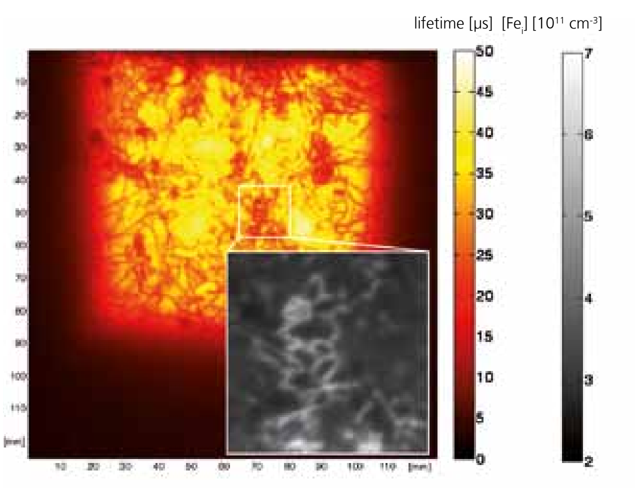


2 *Scanning electron micrograph of a zone with two electric breakdown zones of a multicrystalline solar cell. The detailed measurement on the left shows the electroluminescence signal to localise the breakdown positions. Iron precipitates were identified at these positions with the help of synchrotron X-ray fluorescence measurements (detailed images on the right).*

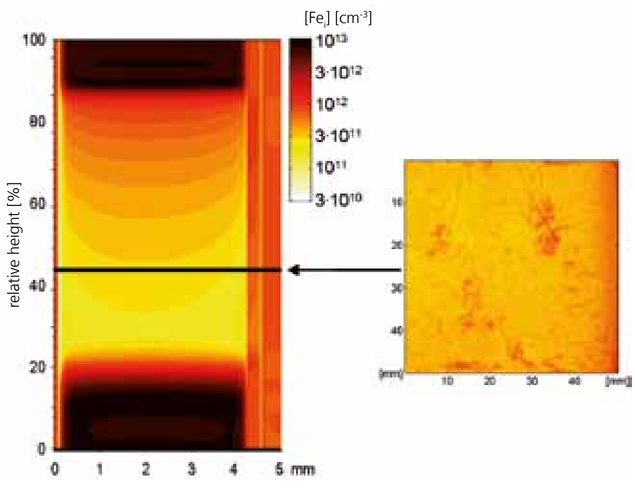
urements, the concentration of iron point defects can thus be determined quantitatively. Figure 1 shows a comparison of the recombination activity and iron precipitate distribution in a model dislocation system for investigation of iron precipitation at crystal defects. The recombination activity of the iron precipitates can be detected by applying photo-luminescence spectroscopy with high resolution (right). Metallic precipitates can not only affect the recombination lifetime, but also be responsible for reverse voltage breakdowns such as occur in partially shaded modules. We were able to detect colonies of iron precipitates at positions exhibiting so-called "soft" diode breakdown (Fig. 2).

Figure 3 shows a lifetime measurement for a multicrystalline silicon wafer from a small block with lower material quality at the edges. The detailed image presents the quantitative absolute concentration of interstitial iron [Fe_i]. We accompany our experimental work with sophisticated multi-dimensional simulations (Sentaurus process) to analyse the experiments and determine parameters contributing to defect formation. Figure 4 illustrates a simulation of interstitial iron distribution after block solidification as a function of the height within the block and the dislocation density, which agrees well with our experimental data.

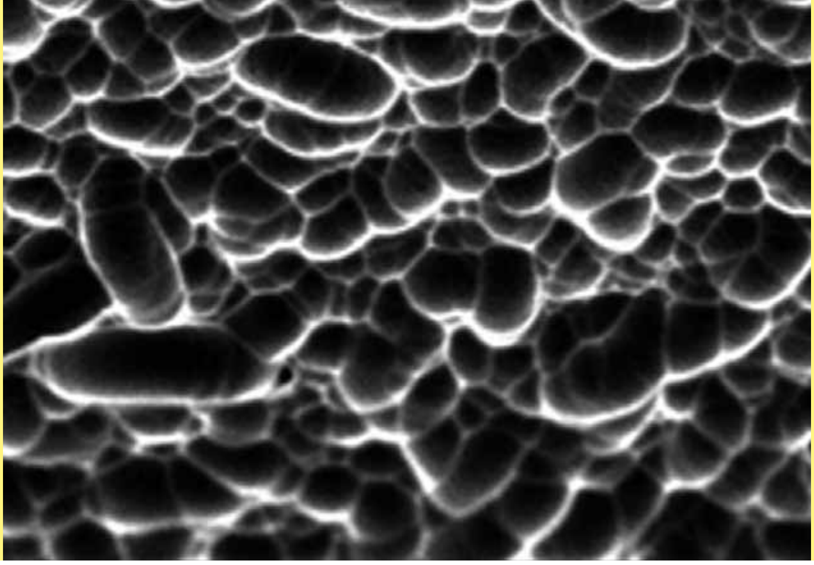
The work was funded within the "SolarFocus" project by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and within the "Silicon Beacon" research project by the Fraunhofer-Gesellschaft. The model dislocation samples in Figure 1 were prepared at the Max Planck Institute in Halle.



3 Measurement of the spatially resolved charge carrier lifetime by photoluminescence imaging and determination of the quantitative concentration distribution of iron point defects (detail).



4 Two-dimensional numerical simulation of the iron point defect distribution after block crystallisation as a function of the height within the block (left). The simulated 2D structure models a typical grain with neighbouring zones with a high dislocation density (orange-coloured vertical stripes). The experimentally determined distribution confirmed the higher concentration of iron point defects along grain boundaries and in areas with a high dislocation density.



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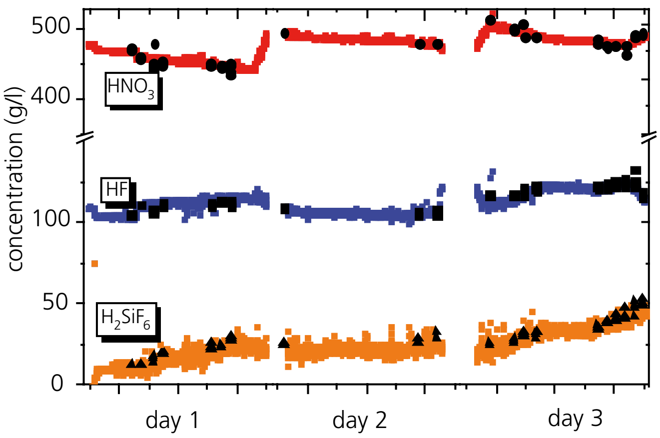
DEVELOPMENT AND ANALYSIS OF WET-CHEMICAL PROCESSES

Wet-chemical processes for solar cell production demand exact controls to guarantee continuously optimal results and to minimise the consumption of chemicals. To this purpose, we have developed various volumetric, chromatographic and spectroscopic procedures to automatically determine the concentration in chemical processing baths. The information obtained is used to develop the processes further.

Katrin Birmann, **Jochen Rentsch**, Martin Zimmer, Ralf Preu

1 *Scanning electron micrograph of the surface of a multicrystalline silicon wafer that was textured in an acidic bath. The clearly recognisable structure increases light trapping in the final solar cell, and thus improves the electrical properties.*



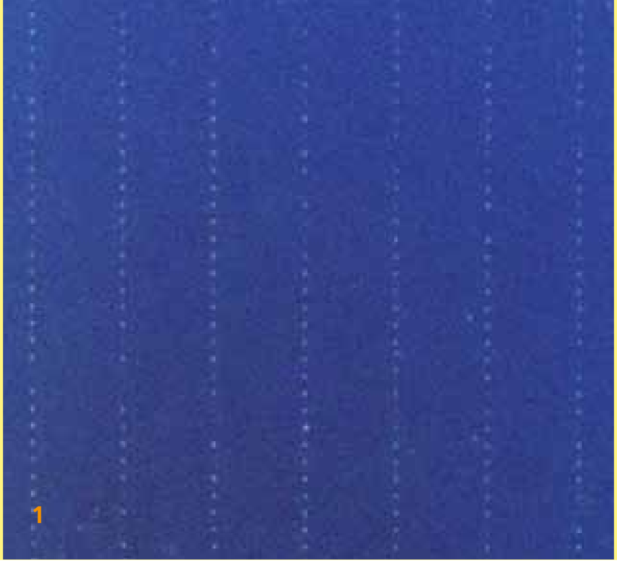
2 *Concentration profile of an acidic texturing bath over three days, determined by NIR spectroscopy. The concentrations of the hydrofluoric and nitric acids are kept constant, while the concentration of dissolved silicon increases.*

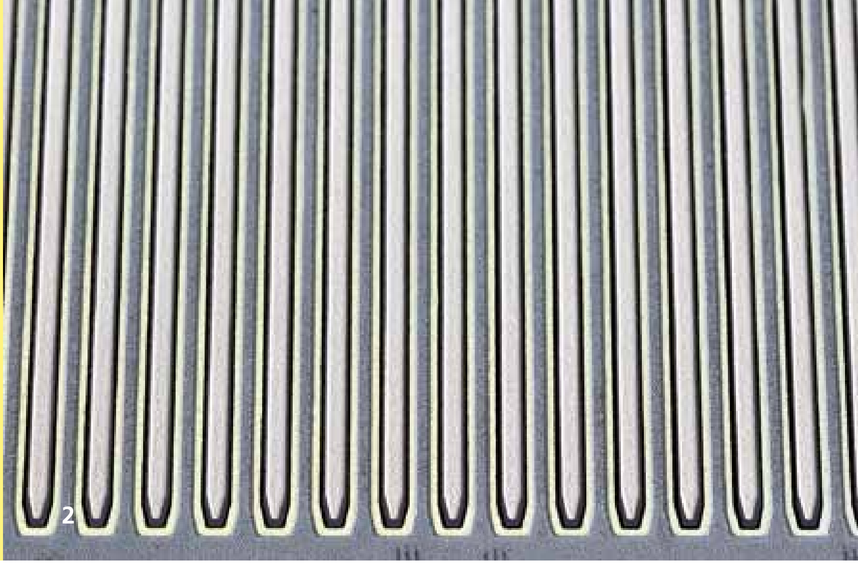
Several wet-chemical processes are typically applied in the production of silicon solar cells. Initially, damage due to sawing is mitigated and the wafer is structured to achieve better light trapping. Multicrystalline silicon is treated with a mixture of hydrofluoric acid, nitric acid and water, whereas monocrystalline material is bathed in an aqueous solution of potassium hydroxide and iso-propanol.

The result depends on the concentration of the chemicals used. However, these are continually consumed during the process, while the concentration of reaction products in the processing solution increases. Optimal process management thus demands accurate monitoring of the existing concentrations. In choosing suitable analytical procedures, not only adequate accuracy but also investment and running costs, and the potential for automation, have to be taken into account.

In our Photovoltaic Technology Evaluation Center (PV-TEC), different processes are being tested with regard to their suitability for process control under industrial conditions. Titration and ion chromatography are applied to automatically identify the solution components in acidic texturing baths. Alkaline texturing baths are analysed with the aid of an acid/base titration combined with measurement of the surface tension. Particular attention is being paid to the application of near-infrared (NIR) spectroscopy. By developing an adapted calibration method, we were able to demonstrate that this very fast and cost-effective method can determine the concentration with high reliability and accuracy.

The work was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Fraunhofer-Gesellschaft.





SCREEN-PRINTED EWT SOLAR CELLS

Printing technology and the pastes used for it are experiencing rapid development due to the growing competition from novel processes and materials. Our contribution demonstrates that this process offers enormous potential for improvement, but at the same time displays the maturity of a fully developed, industrially proven technology. For the first time, we have produced EWT solar cells with an efficiency of up to 18.8 % with screen-printing technology.

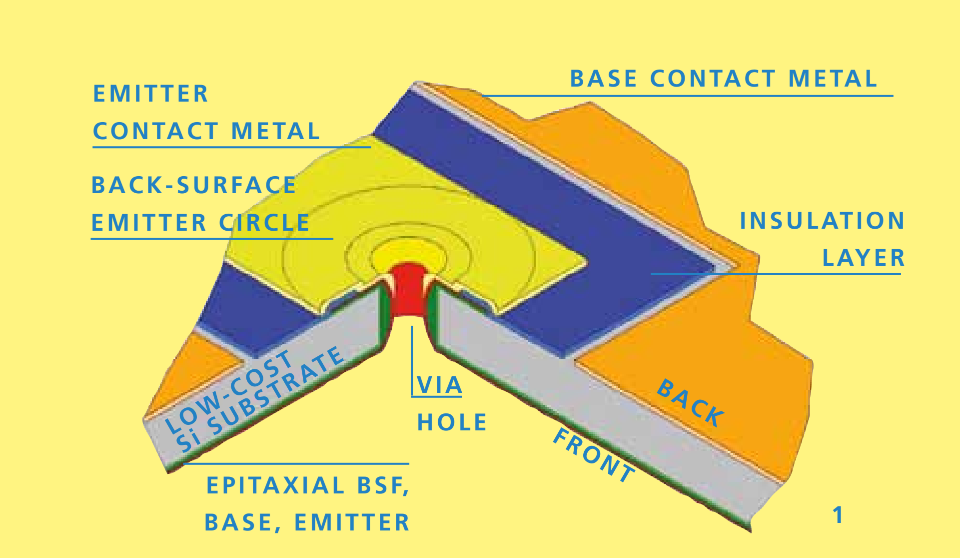
Daniel Biro, Denis Erath, Arne Fallisch, Anne Götz, Roman Keding, Nicola Mingirulli, Marc Retzlaff, Jan Specht, David Stüwe, Sabrina Werner, Ralf Preu

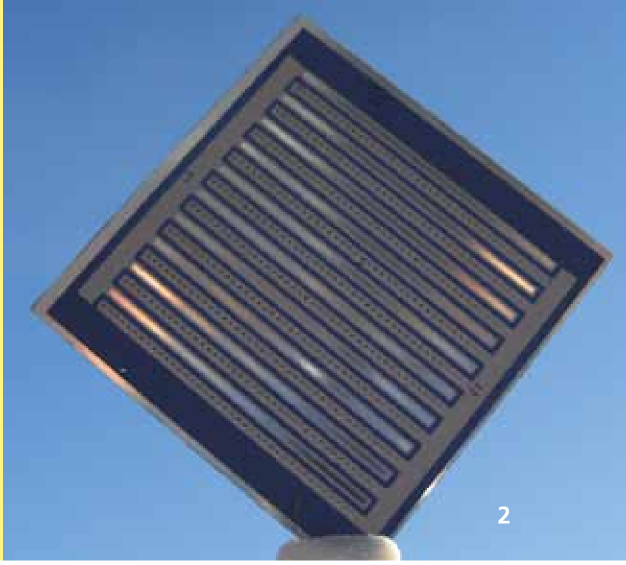
1 *The entire front surface of the EWT solar cell (detail) can be used to convert the incident radiation. The total fraction of the area which is occupied by the perforations is extremely small. As a result, a short circuit current density exceeding 40 mA cm^{-2} can be achieved. (Wafer format: 5 x 5 cm^{2}).*

2 *The back surface of the EWT solar cell features interdigitated contact structures. As the contacts do not cause any shading, they can be dimensioned to minimise losses due to series resistance. Fingers of the same polarity are spaced apart by a distance of app. 1.5 – 2 mm.*

The EWT solar cell (emitter wrap-through) belongs to the family of solar cells with back-surface contacts. Both polarities are accessed on the back surface of the solar cell by interdigitated contact structures. As a result, no shading occurs on the surface of the solar cell facing the sunlight, and the entire area of the solar cell can convert the incident radiant energy. In addition, the series connection of such solar cells is also located completely on the back surface, so that cost-effective "pick and place" processes can be applied within the medium term.

However, the configuration with contacts on the back of the solar cell also poses challenges: On the one hand, a complex circuit of alternating polarity must be created on the back surface, so that electricity generated over the whole area can be efficiently collected and flow to the external contacts. On the other hand, the position of the contacts on the back of the solar cell means that the charge carriers can have long paths within the cell. This situation is less critical in the EWT solar cell, as the EWT solar cell also possesses an emitter on the front surface to collect the charge carriers, which is directly connected electrically to the back surface via a multitude of "vias", laser-cut perforations. For the first time, EWT solar cells with efficiency values up to 18.8 % and an area of 16.7 cm^{2} (without bus bars) have been successfully produced, applying robust screen-printing technology to form the contacts. This became feasible by selecting special screen-printing pastes and adapting the back-surface passivation to the contact-firing process which is applied when thick-film pastes are used. The highly accurate screen-printing equipment which is now available offers sufficient precision to create the required structures.





EPITAXY WRAP-THROUGH: OUR NEW CONCEPT FOR BACK-CONTACT WAFER-EQUIVALENT SOLAR CELLS

Wafer equivalents achieve good solar cell efficiency with relatively impure silicon. Another step toward further cost reduction has been taken by the "Epitaxy Wrap-Through" (EpiWT) concept that we are developing. This unites the idea of wafer equivalents with that of back-surface contacts for solar cells, a technology which has very good chances of becoming a future standard due to the better solar cell performance.

Nils Brinkmann, Elke Gust, Miroslawa Kwiatkowska, Harald Lautenschlager, Emily Mitchell, David Pocza, **Stefan Reber**, Andreas Bett

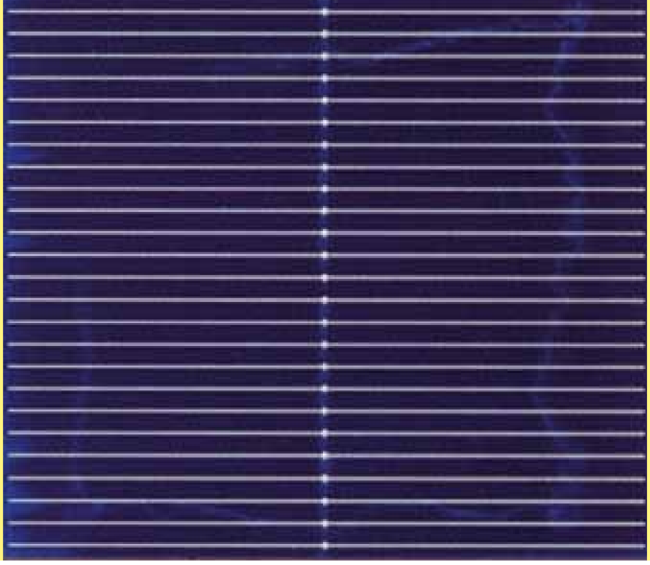
Conventional solar cells, and also wafer-equivalent solar cells, have metal contacts on the front and back surfaces. The contact on the front surface reflects incident light and thus reduces the efficiency of the solar cell. This effect is completely avoided by back-surface contact technology, particularly the "Emitter Wrap-Through" (EWT) concept. Both contacts are located on the back surface, the front surface facing the light is free of shading components and the solar cell can generate almost 10 % more power. In addition, EWT solar cells can be connected more simply and cost-effectively to form a module. To exploit these advantages also for our epitaxial wafer-equivalent technology, we have created and patented the EpiWT concept.

As with standard EWT solar cells, the front-surface emitter of the EpiWT solar cell is connected through so-called "vias", vertical perforations in the solar cell, to the back. The special feature is that not only the emitter layer, but also all of the other thin films of the wafer-equivalent solar cell are guided through the vias to the back surface, as Figure 1 illustrates. This offers several advantages: for example, the entire semiconductor structure of the EpiWT solar cell can be prepared in situ during the silicon epitaxy, and short circuits between the emitter and the substrate are reliably eliminated. In order to transfer the concept to reality, we developed several new processes. Depositing the silicon through the perforations is unique world-wide, meaning that a three-dimensional structure is coated, rather a two-dimensional one, as previously. The result was that we were able to produce structures reliably within the perforations, which can even increase the power gain compared to standard EWT solar cells. The first EpiWT solar cells, which were metallised with cost-effective screen-printing technology, achieved efficiency values of more than 10 %, a good basis for further improvement.

The project was supported within the framework of the "Silicon Beacon" research project by the Fraunhofer-Gesellschaft.

1 *Structure of the epitaxy wrap-through solar cell, viewed from the back surface. The back-surface contacts are reached by so-called "vias" through the inexpensive substrate, where both the base and the emitter are grown epitaxially in situ with high quality.*

2 *Back surface of a complete EpiWT solar cell. The interdigitated contact strips for the base and emitter zones are clearly visible.*



1

METAL WRAP-THROUGH SOLAR CELLS FOR LOW-CONCENTRATION SYSTEMS

Due to the industrially relevant production process, metal wrap-through (MWT) solar cells represent a cost-effective implementation of highly efficient solar cells with back-surface contacts, and are thus suitable for integration into concentrating systems with low concentration factors. At Fraunhofer ISE, maximum efficiency values of up to 18.6 % have already been achieved for monocrystalline silicon under normal illumination. With six-fold concentration and an adapted cell design, efficiency values up to 19.5 % have been measured.

Daniel Biro, **Florian Clement**, Denis Erath, Tobias Fellmeth, Susanne Fritz, Markus Glatthaar, René Hönig, Michael Menkö, Nicola Mingirulli, Gerald Siefer, Benjamin Thaidigsmann, Ralf Preu

To facilitate market penetration, the development of MWT solar cells with back-surface contacts has been deliberately orientated toward the current standard production process for solar cells. The focus of work to date has been on developing MWT solar cells for conventionally constructed modules. The industrially relevant production process that was developed at Fraunhofer ISE allows efficiency values of more than 17 % to be obtained with multicrystalline material.

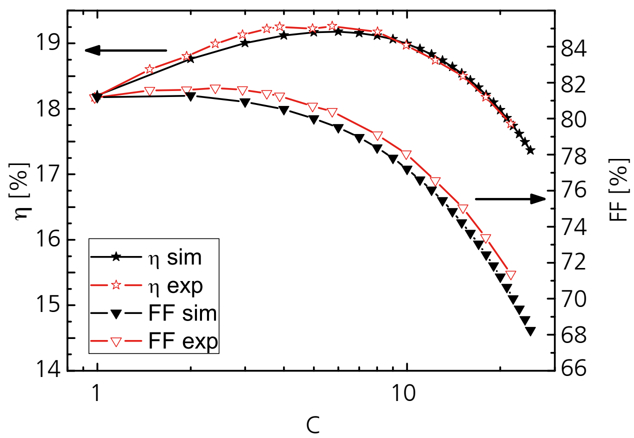
The process was optimised in diverse ways in order to increase the efficiency of MWT solar cells intended for use in low-concentration systems. On the one hand, a screen-printing process was successfully developed to create very fine front-surface contacts (width: ~ 70 µm) with a large aspect ratio (> 0.2). This reduces shading by the front contact grid and increases the series resistance only slightly. On the other hand, an industrially relevant process based on a structured diffusion barrier of silicon oxide was applied to produce the back-surface contact insulation, and has been successfully

1 *Front surface of a monocrystalline MWT solar cell for low-concentration systems.*

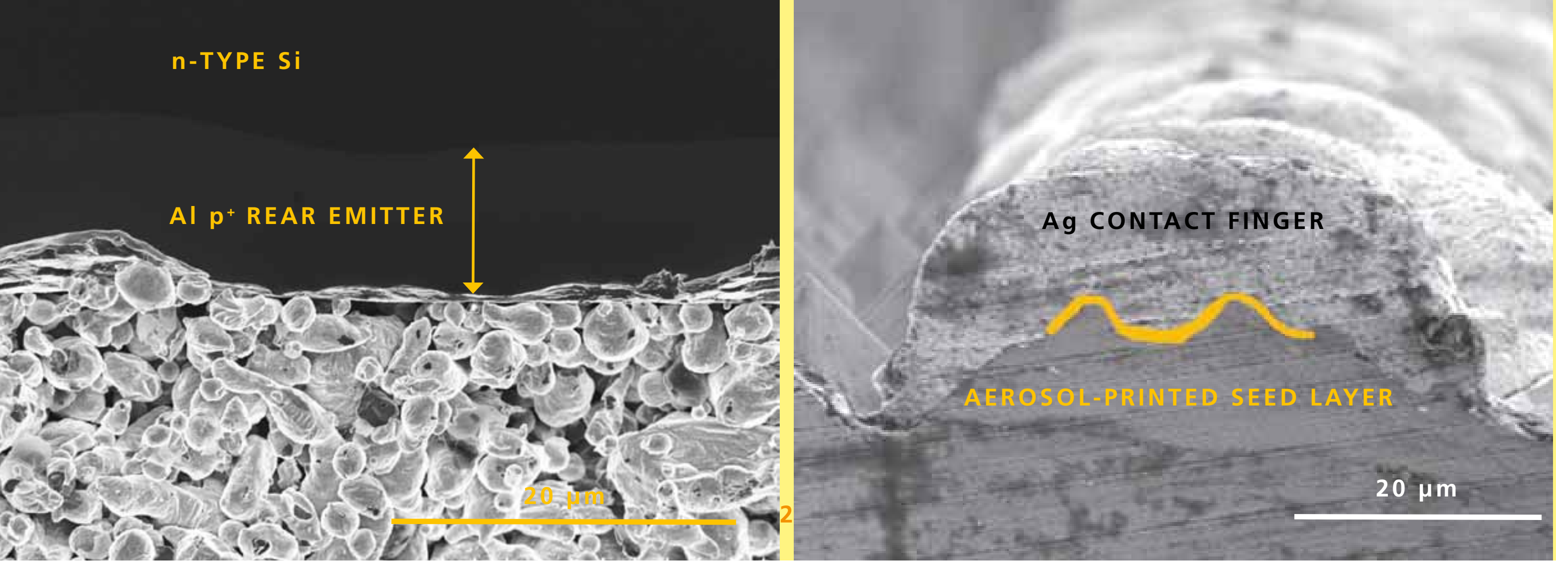
introduced into the manufacturing process. With the help of these processing improvements, efficiency values of up to 18.6 % have been achieved in PV-TEC for monocrystalline material under normal irradiation.

By adapting the cell design, particularly the configuration of the front-surface contact, MWT solar cells were developed specifically for low-concentration systems. Efficiency values exceeding 18 % for concentration factors up to 20 demonstrate the application potential in concentrating systems. With six-fold concentration, the best efficiency values of up to 19.5 % were measured.

The fundamental development of the MWT solar cell in PV-TEC was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).



2 *Example of the dependence of the efficiency η and fill factor FF of a MWT solar cell for different concentration factors C of the incident radiation. Both experimental (exp) and analytically simulated (sim) curves are shown.*

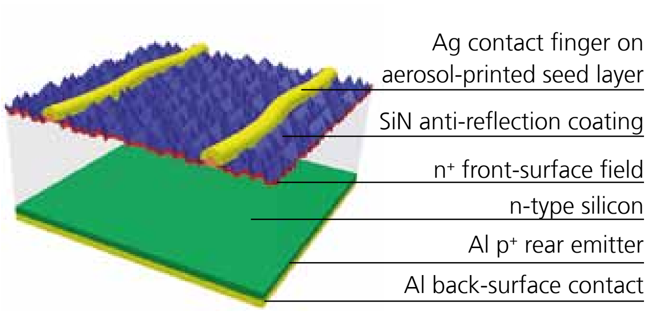


NEAR-INDUSTRIAL N-TYPE SILICON SOLAR CELLS WITH ALUMINIUM EMITTERS

We have developed a special cell structure to exploit the excellent electrical properties of n-type silicon material for highly efficient solar cells that can be industrially produced. This combines a screen-printed aluminium emitter over the entire back surface and an aerosol-printed, silver-plated contact grid on the front surface. We have already achieved efficiency values exceeding 18 % for this rear-junction n-type solar cell with its printed contacts on both surfaces and current collection on the back surface.

Nicole Bayer, Ines Druschke, Denis Erath, Aleksander Filipovic, Martin Hermle, Matthias Hörteis, Norbert Kohn, Nicolas König, Antonio Leimenstoll, Michael Rauer, Marc Retzlaff, Elisabeth Schäffer, Felix Schätzle, Daniel Schmidt, **Christian Schmiga**, Sonja Seitz, Karin Zimmermann, Stefan Glunz

More than 90 % of the industrially produced silicon solar cells today are made of crystalline p-type silicon. This is mainly because the manufacturing process, particularly the phosphorus diffusion to create the emitter, has been established in production lines for many years. Nevertheless,



1 *Schematic diagram of our n-type silicon solar cell with a screen-printed aluminium emitter over the entire back surface and an aerosol-printed and silver-plated contact grid on the front surface.*

2 *Scanning electron micrograph of a cross-section through the aluminium emitter (left) and through a contact finger (right). The thickness of the aluminium p^+ emitter is about 10 µm. The height-to-width ratio of the fingers is about 0.4.*

n-type silicon possesses excellent electrical properties, which are superior to those of p-type material, so that it has gained increasing attention for solar cell development in recent years. As an alternative to a boron-doped p^+ emitter, which is formed by a high-temperature diffusion process, we have developed an aluminium-doped emitter, which is formed by simple screen-printing of an aluminium-containing paste onto the back surface of the cell and a subsequent short alloying step. A major advantage of this procedure and the resulting n^+np^+ cell structure, which allows current collection on the back surface, is that the processing step for the emitter alloying is already applied in production lines for conventional p-type cells for the aluminium back-surface field (BSF).

As effective passivation of the front surface is an important pre-requisite to high efficiency for rear-junction cells, we apply a two-layer metallisation concept here to produce the contact grid of fingers and bus bars, which also allows weakly doped surfaces to be contacted. After the seed layer has been aerosol-printed with a special metallic ink developed at Fraunhofer ISE, the contacts are thickened by light-induced silver-plating. For these n-type solar cells with printed contacts on both surfaces, we have already achieved the best efficiency value world-wide of 18.2 % (150 cm², V_{oc} = 632 mV, J_{sc} = 36.0 mA cm^{-2}). Furthermore, we obtained an efficiency value exceeding 20 % for small cells (4 cm²) with a photolithographically defined contact grid and an additional passivation layer on the emitter surface, demonstrating the great potential of these aluminium p^+ emitters.

The work was supported by Bosch Solar Energy AG.

INDUSTRIAL SOLAR CELLS WITH PASSIVATED AND LOCALLY CONTACTED BACK SURFACES

Solar cells with dielectrically passivated back surfaces and local, laser-alloyed contacts are capable of higher efficiency than conventional solar cells with completely metallised back surfaces. The process developed here makes industrial production of passivated solar cells with efficiency values exceeding 18 % feasible, applying the laser-fired contact (LFC) technology that was developed at Fraunhofer ISE.

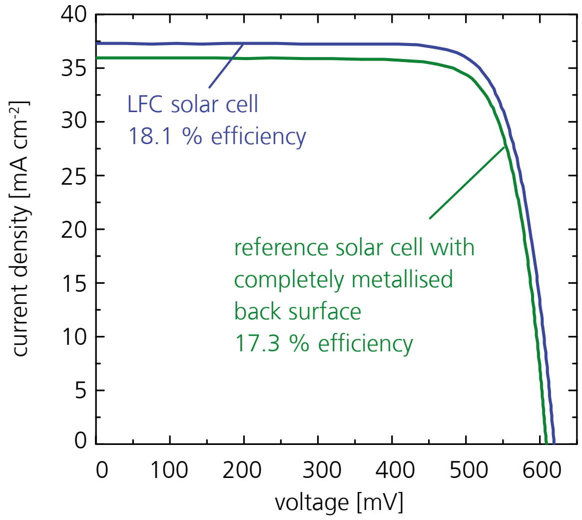
Daniel Biro, Andreas Grohe, Marc Hofmann, Anke Lemke, Sebastian Mack, Jan Nekarda, Jochen Rentsch, **Andreas Wolf**, Edgar Allan Wotke, Ralf Preu

The objective of our Laser-Fired Contact Cluster (LFCC) project is to transfer the technology developed at Fraunhofer ISE for local contacting with laser beams to industrial, screen-printed solar cells. Solar cells with dielectrically passivated back surfaces and LFC feature lower recombination losses and higher light absorptance. Higher efficiency values can thus be achieved with LFC solar cells than with the cells that are currently mass-produced with an aluminium contact covering the entire back surface. Within the LFCC project, a processing sequence to produce LFC solar cells was developed in which much of the conventional manufacturing process can be retained.

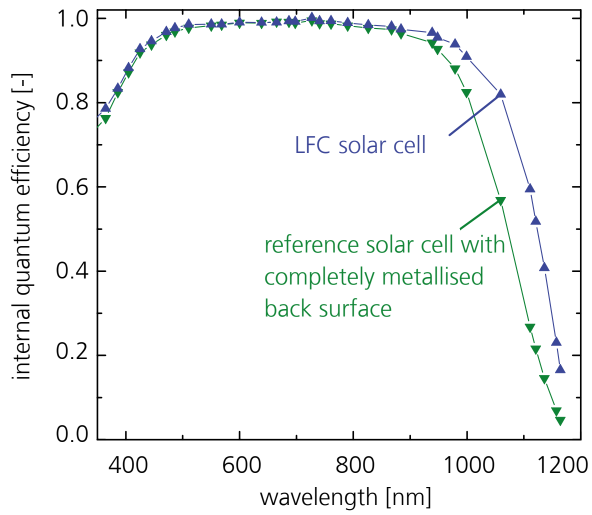
The LFC solar cell is dielectrically passivated by a thermally grown SiO_2 layer of only a few nanometres thickness, which is capped by a coating produced by plasma-enhanced chemical vapour deposition. The front contact grid is applied with screen-printing processes and sintered, just as for conventional cells. An evaporated aluminium layer is used as the back contact, which is locally alloyed through the dielectric layer with the LFC process.

With this cell concept, efficiency values exceeding 18 % were achieved on a demonstration scale in our Photovoltaic Technology Evaluation Center (PV-TEC).

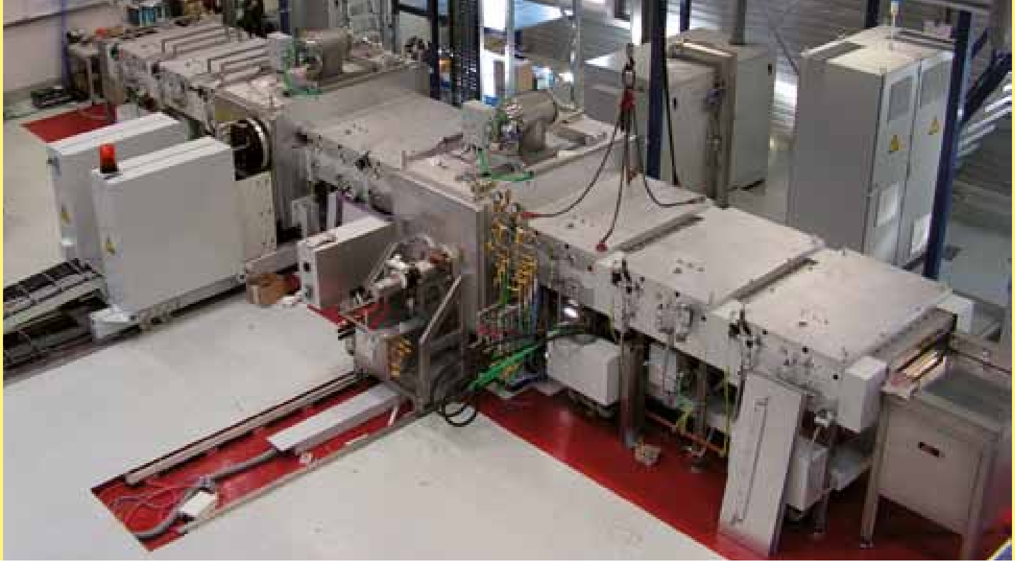
The LFCC project was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and by our project partners, Bosch Solar, Q-Cells, Schott Solar, Solar World and Sunways.



1 *Current-voltage characteristics of an industrially produced LFC solar cell and a reference solar cell with a completely metallised back surface measured under standard test conditions. The dielectrically passivated back surface of the LFC solar cell results in clearly higher values for the short circuit current density and open circuit voltage. The cells of 136 cm² cell area were produced from conventional, boron-doped Czochralski silicon and were stabilised before the measurement by exposure to illumination for 35 hours. Both cells feature soldering pads for interconnection in a module.*



2 *Internal quantum efficiency of an industrially produced LFC solar cell (blue) and a completely metallised reference solar cell (green). The superiority of the passivated LFC solar cell is evidenced particularly by its better performance in the long-wavelength spectral range.*



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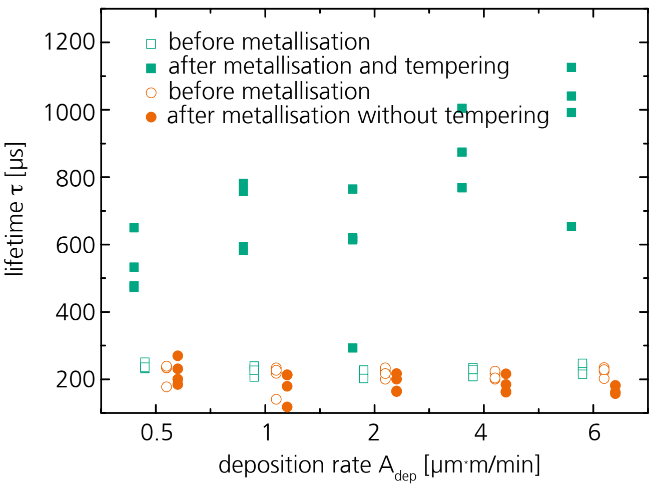
BACK-SURFACE METALLISATION WITH DIELECTRIC PASSIVATION

For solar cells with a passivated back surface, metallisation by physical vapour deposition (PVD) results in lower thermal and mechanical loads than conventional screen-printing technology. Together with our partner, Applied Materials, we have designed equipment for industrial, high-rate deposition of aluminium. Excellent film properties and successful application to high-efficiency solar cells were demonstrated with the pilot line at Fraunhofer ISE.

Andreas Grohe, Philip Hartmann, **Jan Nekarda**,
Dirk Reinwand, Ralf Preu



2 *Results of the quasi-static charge carrier lifetime measurement before and after the deposition of 2 µm aluminium with different deposition rates, with and without a subsequent tempering step at 425 °C for 25 minutes. Float zone (FZ) silicon samples with a base resistance of ρ = 1 Ω cm were used, which had been passivated symmetrically on both surfaces with 100 nm SiO_2. The aluminium layer was etched away from the metallised samples before the measurement.*

1 *In-line pilot system for high-rate evaporation of aluminium coatings for back-surface metallisation of crystalline silicon solar cells with dielectric passivation. Up to 540 wafers per hour can be coated with a film of 2 µm thickness.*

A dielectrically passivated back surface is gaining importance also in the industrial production of solar cells to increase their efficiency. As the back-surface metal coating no longer has to fulfil a passivating function in this case, new approaches can be taken for its production. In the past, many efficiency records have been set for laboratory-scale cells by the use of thin evaporated aluminium films. Together with Applied Materials, we have designed a deposition unit which allows such films to be produced in an inline process with very high deposition rates.

For the process development, we have constructed a pilot system with which we have achieved very high dynamic deposition rates of up to 6 µm*m/min in combination with excellent coating homogeneity. The average deviation of the coating thickness over 576 measurement points for one run is less than 1.5 %, which is more than adequate for all applications identified to date. Its suitability for surface passivation was demonstration by the production and measurement of symmetrically passivated and metallised silicon samples with charge carrier lifetimes of > 600 µs. The first high-efficiency solar cells that were processed with this system immediately featured efficiency values of up to 21.0 %, equalling the potential of the reference process that had previously been used.

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

ATOMIC LAYER DEPOSITION: PASSIVATION OF P-DOPED SURFACES

Effective surface passivation is one of the most important pre-requisites to obtaining high solar cell efficiency. The passivation of p-doped surfaces, particularly surfaces with a high dopant concentration such as occur in a solar cell emitter, has not been satisfactorily solved up to now. By using Al_2O_3 that is applied by Atomic Layer Deposition, this problem has now been solved and excellent passivation of strongly p-doped surfaces has been achieved.

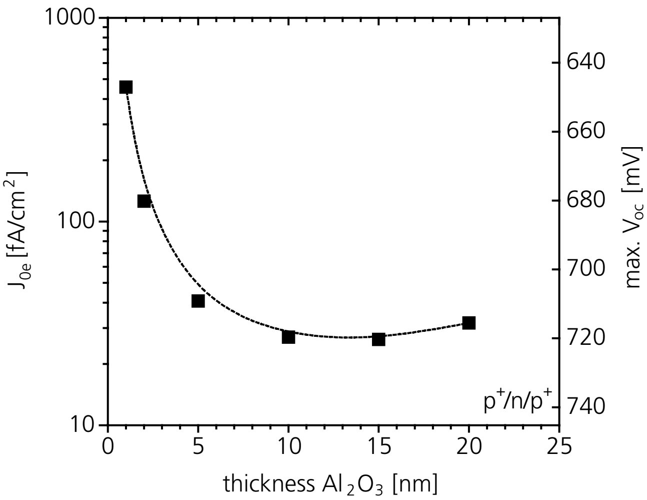
Jan Benick, Martin Hermle, Armin Richter,
Karin Zimmermann, Stefan Glunz

The surfaces of solar cells are usually passivated by dielectric films. On the front surface of the solar cell, this dielectric coating must not only passivate the surface but also minimise its reflectance. Due to its high density of interfacial negative charges (up to app. 10^{13} cm^{-2}), Al_2O_3 provides effective passivation of p-doped surfaces. However, the anti-reflective effect of this coating is not optimal due to its relatively low refractive index (~1.65). To still achieve minimal surface reflection, the Al_2O_3 layer can be additionally coated with a further dielectric film that has a higher refractive index (e.g. SiN_x). In this case, however, the Al_2O_3 layer must be as thin as possible.

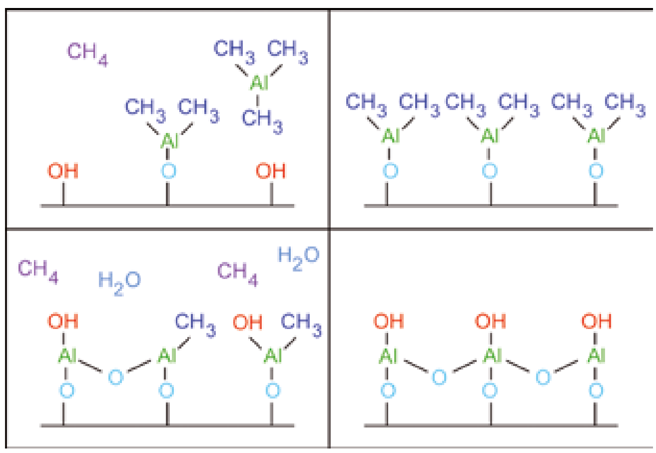
Very high-quality, extremely thin films can be deposited by ALD with perfect control of the film growth. The ALD process is distinguished by the feature that the deposition is based on two self-terminating half-reactions, by which the film is deposited from the vapour phase in a cyclic process. Controlled deposition of films with a thickness of < 1 nm is easily possible with ALD.

Effective passivation of the boron-doped front-surface emitter by Al_2O_3 makes a maximal value of > 700 mV for V_{oc} feasible, even for Al_2O_3 layers with a thickness of only 5 nm. On highly efficient n-type solar cells, in which the front-surface boron emitter was passivated by the dielectric layer stack of 30 nm Al_2O_3 / 40 nm SiN_x, we achieved an efficiency value of 23.4 % (V_{oc} = 703 mV).

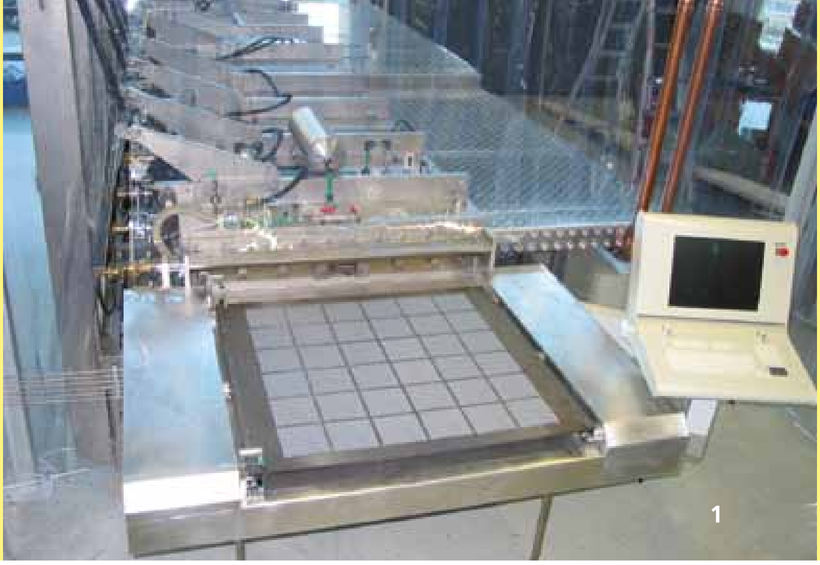
The work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).



1 *Emitter saturation current density and maximal voltage, measured on symmetrical test wafers, in which the boron emitter was passivated by Al_2O_3 films of differing thickness that were applied by ALD. Excellent passivation of the surface was achieved, even with extremely thin films of about 5 nm thickness.*



2 *Atomic layer deposition is based on continuously repeating, self-terminating, vapour phase reactions. The individual phases of an ALD cycle are (from left to right): Self-terminating reaction of reactant 1, purging step to remove reactant 1, self-terminating reaction for oxidation (H_2O or O_2 plasma), purging step to remove the oxidising species.*

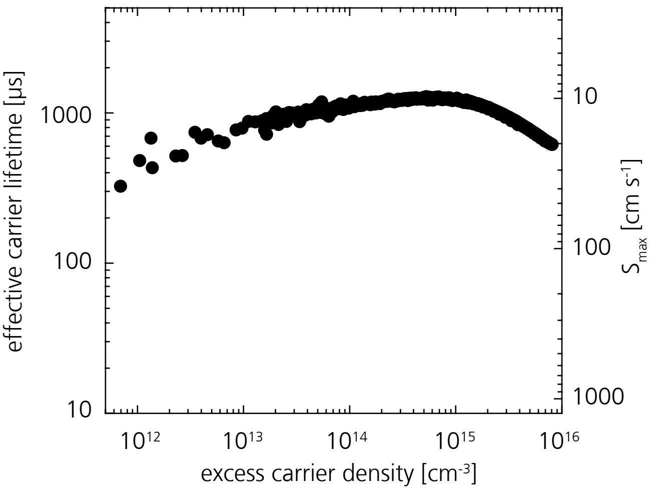


HIGHLY PASSIVATING ALUMINIUM OXIDE PRODUCED BY PECVD

Surface passivation is a key process in the development of highly efficient crystalline silicon solar cells. The plasma-enhanced chemical vapour deposition (PECVD) process developed at Fraunhofer ISE for aluminium oxide (AlO_x) allows dielectric layers with excellent passivation properties to be deposited at the high rates needed for industrial production.

Marc Hofmann, Daniel Kania, Jochen Rentsch, **Pierre Saint-Cast**, Dirk Wagenmann, Ralf Preu

The surface of crystalline silicon wafers can be passivated very efficiently by the deposition of aluminium oxide (AlO_x). Up to now, the atomic layer deposition method (ALD) has been favoured, which allows controlled deposition, resulting in excellent film properties. However, the deposition rate for this method is limited, as the deposition occurs as individual mono-layers of aluminium and oxygen atoms. Therefore, industrial deposition at present is restricted to very thin films and processing equipment with a high wafer throughput has yet to be developed.



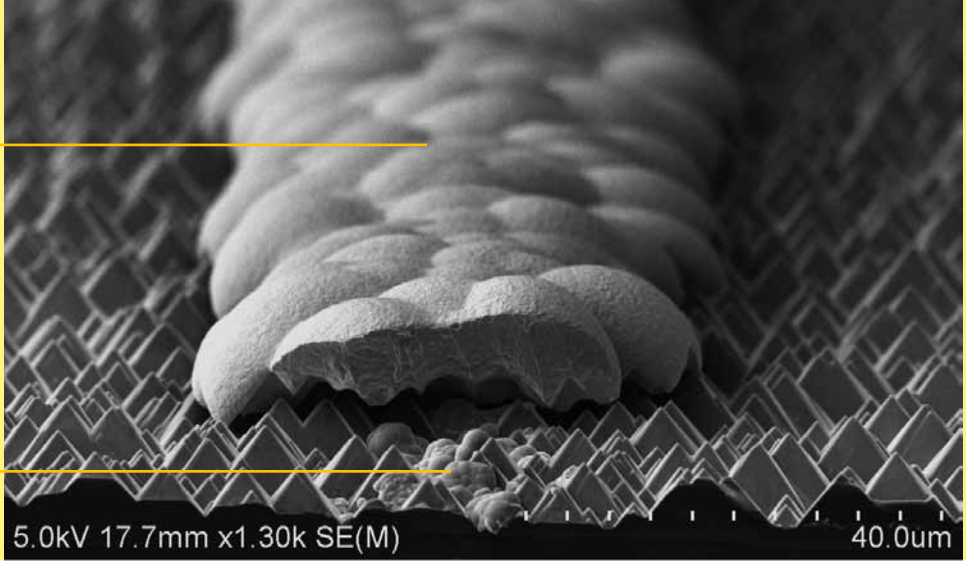
2 *Result of a transient measurement of charge carrier lifetime for a silicon wafer (boron-doped, specific base resistance of 1 Ω cm, thickness of 250 µm), which is coated on both sides with app. 50 nm of AlO_x applied by PECVD.*

1 *Prototype of PECVD equipment from the Roth&Rau company, which is used for high-rate deposition of aluminium oxide layers for surface passivation of crystalline silicon solar cells (6 x 6 wafers with an edge length of 125 mm).*

The plasma-enhanced chemical vapour deposition (PECVD) process which we present allows a very high AlO_x deposition rate of app. 80 nm/min to be achieved. By comparison, the rate for ALD is approximately 1 nm/min. We developed our process with equipment which is used industrially to deposit amorphous silicon nitride films as an anti-reflective coating on solar cells. The fundamental process was developed with extremely pure silicon samples doped to usual industrial concentrations. With these samples, we have already achieved excellent effective surface recombination rates of less than S_{eff} = 10 cm s^{-1} on silicon substrates. Furthermore, we were able to show that the passivation is primarily due to the high density of immobilised negative charges in the layer (~2 x 10^{12} cm^{-2}), which leads to advantageous band bending in the silicon.

The excellent film properties combined with the high-rate deposition represent an important milestone along the route toward industrially produced, highly efficient crystalline silicon solar cells with a simple structure.

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



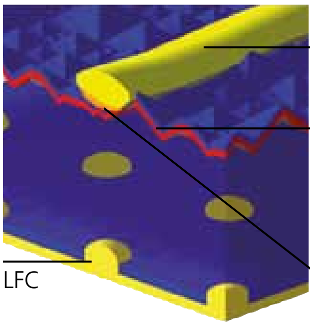
EXTREMELY EFFICIENT SILICON SOLAR CELLS WITH NICKEL-PLATED CONTACTS

The most efficient way to reduce the cost of photovoltaic power generation is to increase the efficiency value. Optimisation of the front contacts plays a central role in this task for silicon solar cells. By applying a processing sequence of laser ablation, nickel-plating and light-induced silver-plating, we have succeeded in preparing very fine, highly conductive contacts and thus increasing the solar cell efficiency to values exceeding 20 %.

Monica Alemán, Jonas Bartsch, Norbert Bay, Sebastian Binder, Andreas Grohe, Annerose Knorz, Ralf Preu, Elisabeth Schäffer, Christian Schetter, Daniel Schmidt, **Stefan Glunz**

Two major loss factors for industrial solar cells are caused by the front contact grid, namely shading and resistance losses. We are thus working intensively on an industrially applicable technology to manufacture novel, optimised contacts. In many cases, this type of contact system is based on a two-stage process, i.e. deposition of a seed layer, which creates the electric contact to the cell, and subsequent galvanic plating with silver or copper to achieve adequate transverse electrical conductivity. The seed layer can be printed as a fine line and then fired, or electrochemically plated. In the latter case, however, the anti-reflective coating of silicon nitride (SiN_x) must first be opened. An interesting technique to do so is ablation of the SiN_x layer with a laser beam. Although this method operates very elegantly and without direct contact, it is imperative that the very thin phosphorus emitter (0.2 – 0.3 µm) directly below the cell surface not be damaged. The process that we have developed fulfils this criterion excellently, even for textured surfaces.

1 *Scanning electron micrograph of a contact which was produced by laser ablation of the SiN_x layer, nickel-plating and light-induced silver-plating.*



2 *Structure of a solar cell with nickel-plated contacts.*

In the following step, nickel is deposited on the opened regions in a galvanic bath. We also had to investigate this processing step very intensively and optimise it, as nickel can easily penetrate into the cell and damage the emitter and thus the entire cell. After the nickel seed layer has been finally plated with silver, the structure shown in Figure 1 is obtained. The contacts that are produced with our processing sequence are very narrow and have an excellent aspect ratio. If these contacts are used on high-efficiency cell structures (Fig. 2), very good efficiency values of up to 20.7 % can be achieved (V_{oc} = 651 mV, J_{sc} = 39.4 mA cm^{-2}, FF = 80.7%). Such values are otherwise obtained only with laboratory technology. Particularly in combination with copper-plating, which we are studying intensively at present, this contact structure is very attractive with regard to costs and the potential for high efficiency.

LASER CHEMICAL PROCESSING: SELECTIVE EMITTER STRUCTURES FOR SOLAR CELLS

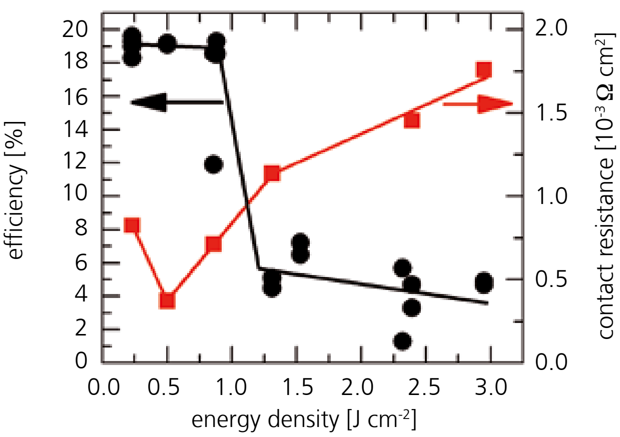
If the doping concentration for the emitter of a solar cell is reduced, the efficiency can be increased significantly. However, at the same time it becomes difficult to produce contacts on such an emitter with industrial metallisation procedures. The contact resistance between metal fingers and the emitter can be reduced by creating selectively highly doped zones. With laser chemical processing (LCP), locally highly doped zones can be produced without additional high-temperature or masking steps.

Kristine Drew, Andreas Fell, Christoph Fleischmann, **Filip Granek**, **Sybille Hopman**, Kuno Mayer, Matthias Mesec, Andreas Rodofili, Stefan Glunz

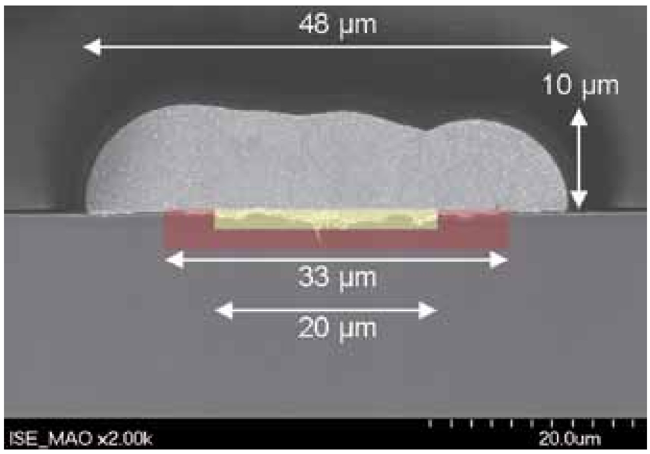
Laser chemical processing (LCP) is affected by numerous laser and liquid parameters. For the LCP system that we use, these include pulse energy, pulse separation, laser wavelength, dopant concentration and flow rate. This makes it all the more important to determine an optimal parameter range.

In order to identify the optimal pulse energy range, experiments were carried out with a high-efficiency solar cell structure with evaporated metal contacts. In this way, even a slight disturbance to the space charge zone by laser-induced damage can be detected. Figure 1 shows the efficiency of the processed solar cells as a function of the energy density. The abrupt decrease in efficiency at around 1 J cm^{-2} is obvious. With the aid of transmission electron microscopy (TEM), a higher dislocation density could be demonstrated in the cells that had been subjected to high energy density. They were caused by the laser process and disturbed the pn junction. The same graph also shows the contact resistance as a function of the energy density. The optimal contact resistance is also found at low values of the pulse energy, which is also very advantageous for industrial application of the process. As a result, a single laser could supply several jet nozzles with laser radiation. Figure 2 shows a metal contact which was produced by galvanic thickening of an aerosol-printed seed layer after selective high doping with LCP. The resulting contact resistance was < 10^{-3} Ω cm^2.

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



1 *The black circles represent the solar cell efficiency as a function of the laser energy density. The red squares show the contact resistance of the evaporated metal contacts as a function of the energy density. The best contact resistance values occur in the same energy density range as the best efficiency values.*



2 *Scanning electron micrograph of a galvanically thickened aerosol-printed seed layer (20 µm). The marked lengths indicate the width (48 µm) and height (10 µm) of the contact as well as the LCP-doped zone (33 µm). Contact resistance values of < 10^{-3} Ω cm^2 were achieved with this front contact structure.*

SILICON HETEROJUNCTION SOLAR CELLS FOR INDUSTRIAL PRODUCTION

Silicon heterojunction solar cells present a cost-effective alternative to achieve high cell efficiency values. The goal of our work at the Laboratory and Service Center in Gelsenkirchen is to develop an industrial manufacturing process for this type of solar cell. In doing so, we achieved an efficiency value of 15.3 % for an area of 100 cm² for p-type material and 16.1 % for an area of 25 cm² for n-type base material.

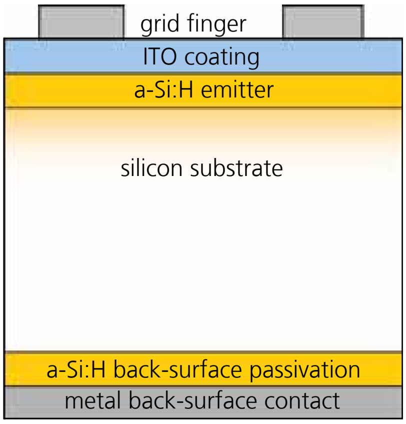
Dietmar Borchert, Sinje Keipert, Stefan Müller, Markus Rinio, Petra Schäfer, Leilei Xia, Raif Zejnelovic, Johannes Ziegler, Ralf Preu

a-Si/c-Si silicon heterojunction solar cells consist of monocrystalline base material, which has been coated on the front and back surfaces with thin films of amorphous silicon or related materials. Figure 1 shows the schematic structure of such a cell. A processing temperature of 250 °C is not exceeded during the entire manufacturing process. The amorphous layers on the front and back surfaces provide very good surface passivation, which makes high efficiency values feasible.

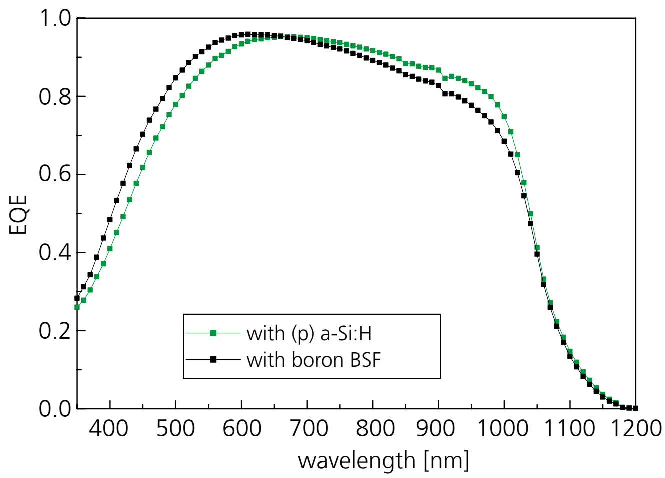
The goal of our work is to develop an industrial manufacturing process for this type of solar cell. To this purpose, we have systematically extended our technology over recent years, so that we can now carry out all processing steps for areas of 125 mm x 125 mm. We achieved an efficiency value of 15.3 % for an area of 100 cm² of p-type Czochralski silicon. In this cell, a conventional boron back-surface field was applied for back-surface passivation.

In the next step, we were able to replace this type of passivation by a passivation layer of p-doped amorphous silicon. Figure 2 compares the external quantum efficiency curves for these two cases. The amorphous silicon passivates the surface just as well as the conventional boron back-surface field. This is also proven by the open circuit voltages. We achieved 630 mV for both cells.

Together with our co-operation partner, the Chair of Electronic Devices at Hagen Open University, we have produced heterojunction solar cells on non-textured n-type float-zone silicon wafers with an area of 25 cm². We achieved an open circuit voltage of 697 mV and a cell efficiency value of 16.1 %.



1 *Structure of an a-Si/c-Si heterojunction solar cell. The thin emitter layer and the back-surface passivation layer of amorphous silicon are deposited in succession onto a monocrystalline silicon substrate. An additional indium tin oxide (ITO) layer guarantees good transverse electrical conductivity between the grid fingers on the front surface. The metal coating on the back surface usually consists of aluminium.*



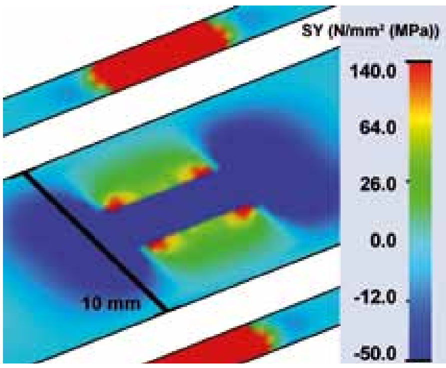
2 *Comparison of the measured external quantum efficiency (EQE) for a heterojunction solar cell with a conventional boron back surface field (BSF – black line) and one passivated by a p-conductive amorphous silicon layer (green line) on the back surface. The agreement between the curves at long wavelengths indicates that both passivation techniques have an identical effect.*

1


ESTABLISHMENT OF THE PHOTOVOLTAIC MODULE TECHNOLOGY CENTER

With the support of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Fraunhofer ISE has established a technology centre for photovoltaic modules in Freiburg (Fig. 1). The new platform is equipped with a unique palette of experimental and analytical technology. The Photovoltaic Module Technology Center (MTC) closes the gap between laboratory development and industrial production technology.

Marco Tranitz, Harry Wirth, Werner Platzer



2 *Calculated stress distribution in cell connectors (top and bottom) and cell (centre) near a soldering point after cooling to room temperature. The tensile stresses in the cell (red) are particularly critical.*

1 *View inside the MTC with the X-ray unit and the tabber-stringer for fully automatic cell connection.*

Experimental platforms

The electrical connections between solar cells are critical for the performance and reliability of modules. Particular attention must be paid to the formation of inter-metallic phases and the reduction of material stresses during cooling. We use experimental soldering platforms that include laser, induction, ultrasonic and contact soldering to investigate and optimise soldering processes, as well as adapting them to new materials. Laminators with usable areas of 1700 mm x 1000 mm are available for module production.

Characterisation

Comprehensive characterisation at all stages of production allows targeted process optimisation. Graduated power measurements and electroluminescence imaging are applied to track the performance and integrity of the cell from initial delivery, through string production and encapsulation, to the module that has been subjected to accelerated aging.

Modelling

We apply finite element models (FEM) to calculate thermo-mechanical stresses in the components. In module production, the cooling of the joined materials is particularly critical (Fig. 2). Additional thermal and mechanical loads occur once the module has been installed for use. Electrical series-resistance losses for complex components can be modelled by equivalent circuits. In addition to the electrical efficiency of the cell connection, the optical efficiency of the entire system is modelled so that finally, the module efficiency can be optimised.

DEVELOPMENT OF MODULE TECHNOLOGY FOR BACK-CONTACTED CELLS

In co-operation with our partners, Schmid Technology Systems, Aleo Solar, Somont and Swiss Solar Systems, module production technology was developed for rear-contact cells and demonstrated in module formats from 16 to 24 cells. The series resistance losses in the cell connections can be reduced from 3 % in the conventional module configuration to 1 % using materials that caused only moderate cost increases.

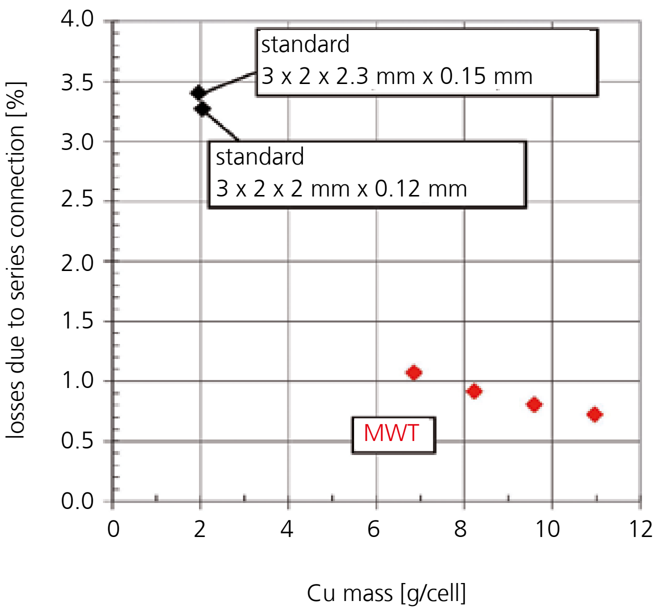
Carsten Malchow, Marco Tranitz, **Harry Wirth**, Werner Platzer

Many developments on solar cells are concerned with transferring all electrical contact points to the back surface of the cell. Rear-contact cells have little or no shading losses, and the series-resistance losses in the cell and the cell connector can be reduced. Finally, these cells make it feasible to produce modules quickly and reliably, even with very thin cells. Our project aimed to develop connection materials and processes which allowed these advantages to be effective.

Particularly in the case of MWT cell technology (Metal Wrap-Through), the ohmic losses which are created by series connection of the cells can be clearly reduced by larger cross-sections for the connectors (Fig. 2). The resulting increase in yield more than compensates the additional costs for copper. The layout of the cell connectors was designed to make optimal use of the connector cross-section for a given current density. In addition, we demonstrated that the thermo-mechanical load on the cells could be reduced by more than 90 % by suitable structuring and configuration of the cell connectors.

A large-area cell connector was developed for mounting the cells, which allows the encapsulation material to be distributed during the lamination process. Primarily materials were used which have already proven themselves in module constructions. An important goal was the use of lead-free solder. The prototype modules have withstood accelerated aging tests, including temperature cycling and damp heat testing in analogy to EN 61215.

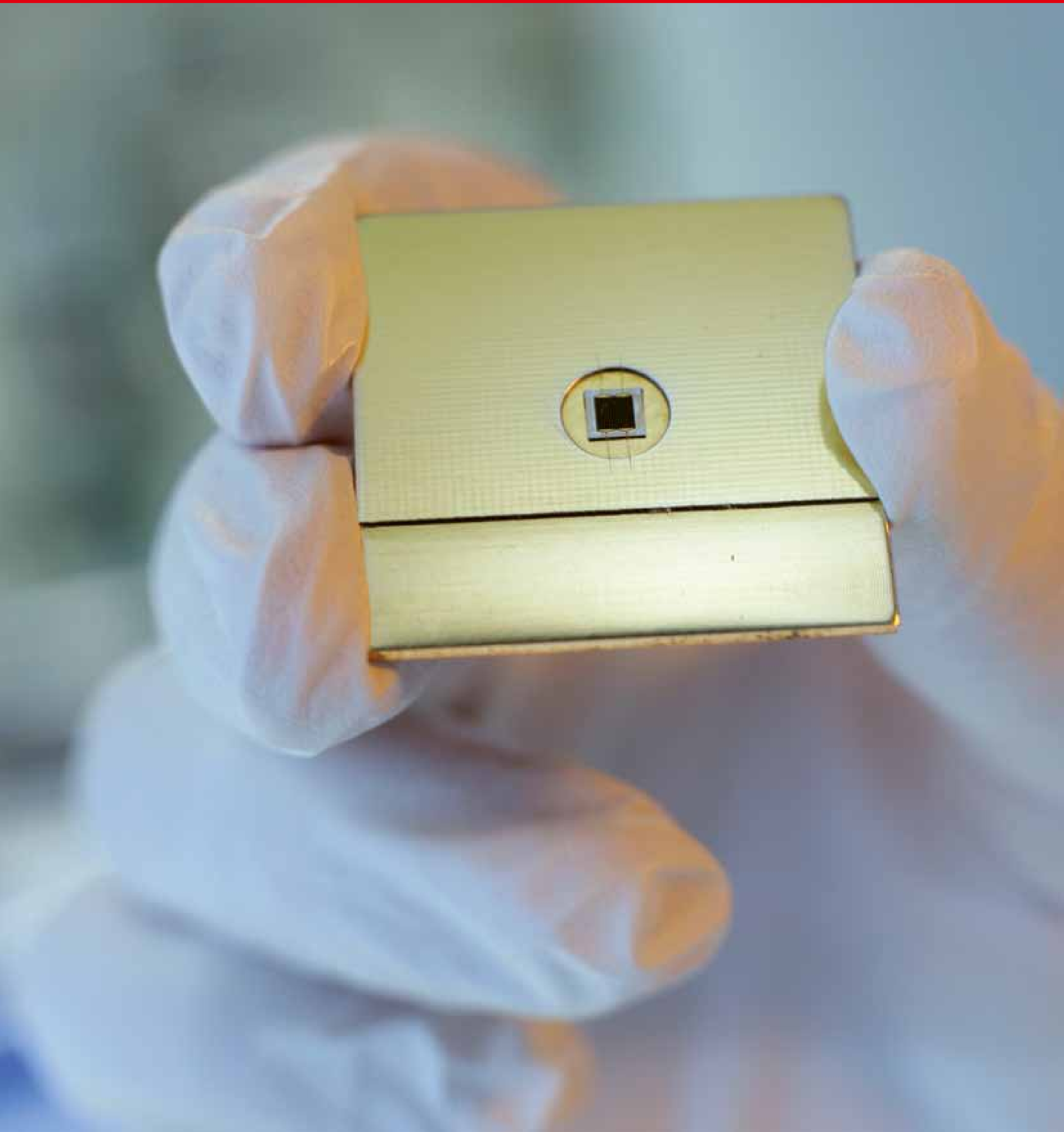
1 *Module with 16 rear-contact cells of the MWT type. The cells were produced by Bosch Solar and Fraunhofer ISE.*



2 *Calculated series resistance losses in standard and MWT cell strings, as a function of the amount of copper (Cu) used. Standard cells are connected with 2 – 3 flat cell connectors with the specified cross-section per edge.*

The work described here was carried out as part of a project that was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

ELECTRICITY FROM SUNLIGHT



ALTERNATIVE PHOTOVOLTAIC TECHNOLOGY

Complementing the work on silicon photovoltaics (see p. 49), our research and development on solar cells also extends to other types of photovoltaic technology: III-V semiconductors, dye solar cells and organic solar cells.

III-V semiconductors and their application fields

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 of all types of 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. 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. For terrestrial use, we are developing concentrator cells for the highest optical concentration factors of up to 2000 and efficiency values of around 40 percent. For instance, we are also designing monolithically integrated modules (MIM), in which several small cell units are connected in series at the wafer level. This type of cell is used in parabolic-reflector concentrator systems and in solar power towers. In addition to developing cell processes for industry, we also adapt concentrator solar cells to the specific requirements of our clients.

A further focus within our work on concentrator solar cells is the development of appropriate characterisation techniques and instruments for application in industrial production. An example is a newly developed measurement facility, which allows concentrator modules to be measured in the laboratory for the first time. CalLab PV Cells offers also calibrated measurements of multi-junction solar cells. Furthermore, we develop complete concentrator module and system packages. The FLATCON® technology, which was developed at Fraunhofer ISE, is one example. It is now being produced successfully by the spin-off company, Concentrix Solar GmbH. In the Concentrator Technology and Evaluation Centre ConTEC, we develop appropriate production process technology for our industrial clients.

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.

Scientists at Fraunhofer ISE achieved an efficiency value of 41.1 percent for the conversion of sunlight into electricity for the first time in 2009, setting a new record. Sunlight was concentrated by a factor of 454 onto a tiny multi-junction solar cell of III-V semiconductors with an area of 5 mm^2. Sub-cells made of the materials GaInP, GaInAs and Ge were used. These III-V multi-junction solar cells, which were developed at Fraunhofer ISE, consist of up to 40 different layers, which are grown epitaxially as a stack by metal organic vapour phase epitaxy (MOVPE). The highly efficient multi-junction solar cells are used in photovoltaic concentrator systems for solar power stations in countries with a high proportion of direct sunlight. At Fraunhofer ISE we are currently pursuing various research approaches to improve the efficiency of multi-junction solar cells made of III-V semiconductors (see article on p. 76 ff).

CONTACTS

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INCREASING THE EFFICIENCY AND UPSCALING ORGANIC SOLAR CELLS

Improving the cell efficiency and developing cost-effective production processes are two main aspects of the work at Fraunhofer ISE to develop organic solar cells toward commercial maturity. New organic semiconductors with the potential for higher efficiency are continually being investigated. In order to produce organic solar cells cost-effectively, new cell and module concepts are being developed which allow the material and processing costs to be minimised without causing significant decreases in efficiency.

Sebastian Mühlbach, Hans-Frieder Schleiermacher, Matthias Schubert, Clemens Veit, **Uli Würfel**, **Birger Zimmermann**, Werner Platzer

1 *Flexible organic solar cell module with an inverted stack sequence, without indium tin oxide. We have connected eleven cells in series to ensure that a sufficiently high voltage is reached even at low light intensities. With P3HT:PCBM, we thus obtain a voltage of 6.5 V under full solar irradiation.*

In contrast to conventional solar cells of inorganic semiconductors, light absorption in organic solar cells does not result in free electron-hole pairs but in quite strongly bound excitons. To separate the charges, a second material has to be added. One of the charge carriers can then be transferred to this acceptor. During this charge transfer, some of the energy is dissipated and thus the voltage of the solar cell is reduced. In recent years, the Konarka and Solarmer companies in the U.S.A. increased the efficiency of organic solar cells to more than 6 % by adapting the materials appropriately. The P3HT:PCBM donor/acceptor system, which is most commonly used at present, allows a cell voltage of app. 0.6 V.

Co-operating with universities in Linköping and Peking within the "Morphoso" project, we have achieved an efficiency value of 5.4 % with a new polymer. This results from better band-matching with the HXS-1:PCBM combination, whereby we obtain an open circuit voltage of app. 0.8 V without reducing the short circuit current.

With regard to up-scaling, we have succeeded in producing inverted organic solar cell modules with promising efficiency of the active cell area. In particular, we reached the highest fill factor world-wide for flexible organic solar cells of 64 %. In the "Flexensys" project, the modules supply power to an autonomous sensor system which is intended to be mounted in a jacket. An important advantage is that our inverted cell structure avoids the use of expensive indium tin oxide electrodes, which are otherwise generally applied.

Both projects are supported by the German Federal Ministry of Education and Research (BMBF).

MODULES AND PRODUCTION TECHNOLOGY FOR CONCENTRATOR PHOTOVOLTAICS

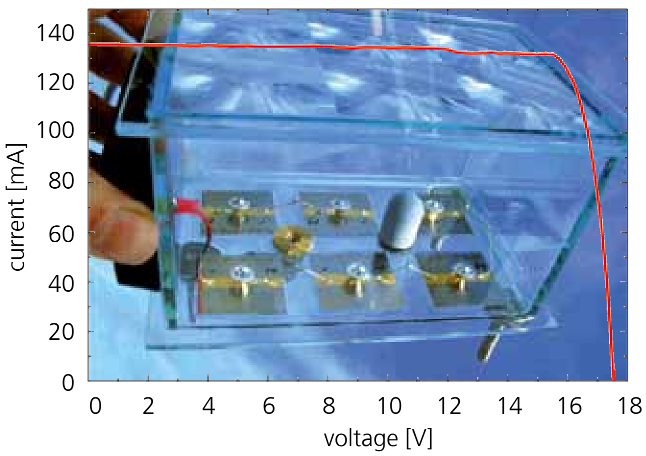
Concentrator modules with III-V multi-junction solar cells achieve the highest module efficiencies among all types of photovoltaic technology today. The most recent example is our record for this year of 29.6 %. Concentrating photovoltaic technology encompasses many diverse concepts but demands adapted production technology. We are working to meet this challenge in the Concentrator Technology and Evaluation Center (ConTEC) at Fraunhofer ISE.

Armin Bösch, Alexander Dilger, Frank Dimroth, Fabian Eltermann, Juan Pablo Ferrer Rodríguez, Henning Helmers, Joachim Jaus, Michael Passig, Gerhard Peharz, Gerald Siefer, Stefan Thaller, Patrick Uhlig, Maike Wiesenfarth, Oliver Wolf, Christopher Zuckschwerdt, **Andreas Bett**

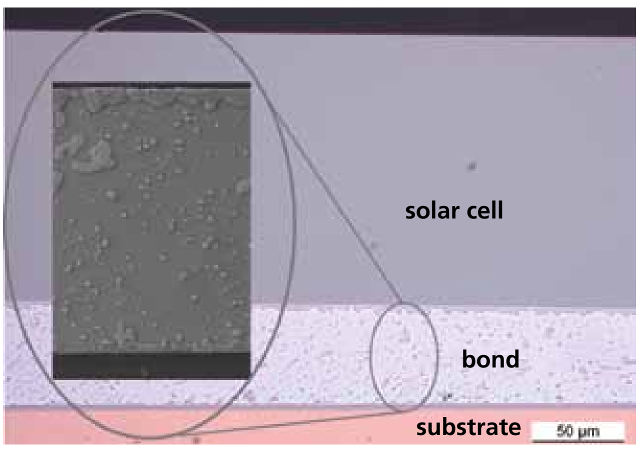
In ConTEC we are developing production processes for concentrator modules. In 2009, we focussed on developing a production process to integrate a second optical stage in our FLATCON® modules. The second optical stage consists of a funnel-formed reflector. With this extension, the acceptance angle of the module can be increased and more radiation can be concentrated onto the cell. As a result, the efficiency of the concentrator modules is increased. Figure 1 shows a module with secondary optics and the measured current-voltage characteristic curve. Module efficiency values of up to 29.6 % were achieved in real operation – a new record value. The modules include triple-junction solar cells that were produced at Fraunhofer ISE.

Further development of bonding technology is another focus at ConTEC. It is particularly important for concentrator modules, as the thermal behaviour of the module is determined essentially by the coupling of the concentrator solar cell to the substrate. On the one hand, we determine this thermal behaviour by measurement; on the other hand, simulation models allow us to predict the performance. Figure 2 shows a typical configuration. A solar cell is mounted with a bonding layer onto a substrate. We are investigating various adhesive and soldered bonds, and are optimising the processing sequence so that durable and stable connections result. To test them, accelerated aging experiments are also being developed at ConTEC.

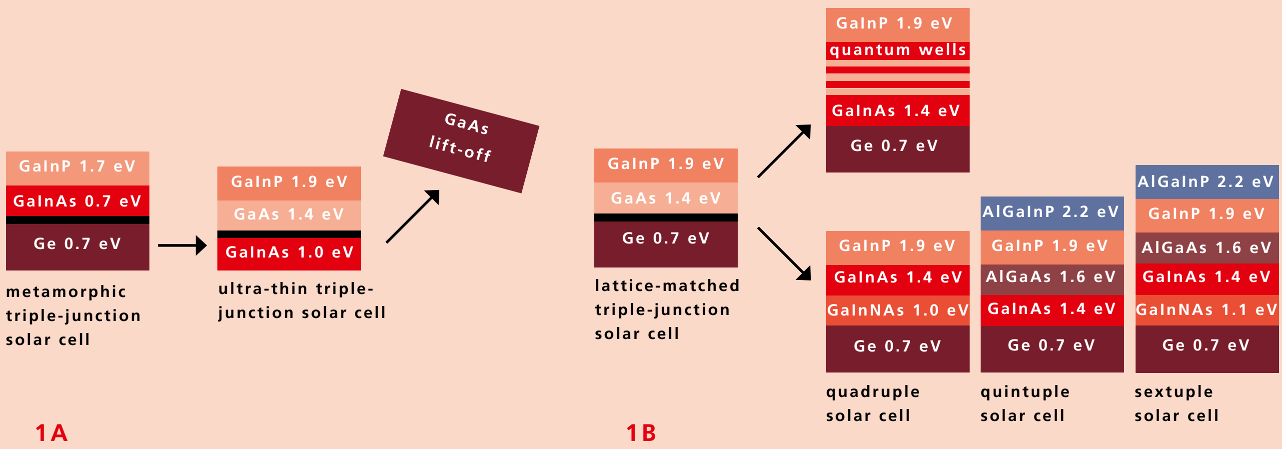
Our work is supported by the EU, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the "Deutsche Bundesstiftung Umwelt" (DBU) and industrial partners.



1 *FLATCON® test module with secondary optics and the current-voltage characteristic measured on 16.06.2009. An efficiency value of 29.6 % was measured with direct normal irradiation of 718 W m^{-2}, an ambient temperature of T = 20.5 °C and a wind speed of 0 m s^{-1}. The characteristic parameters were: I_{sc} = 136 mA; V_{oc} = 17.5 V; FF = 85.5 %.*



2 *Cross-section of the structure: Solar cell – bond – substrate viewed under a light microscope. The bonding layer was investigated with finer resolution in a scanning electron microscope (insert). Good and stable connection technology is essential for concentrator solar cells, as heat must also be removed via this bond.*



HIGHLY EFFICIENT MULTIPLE SOLAR CELLS OF III-V SEMICONDUCTORS

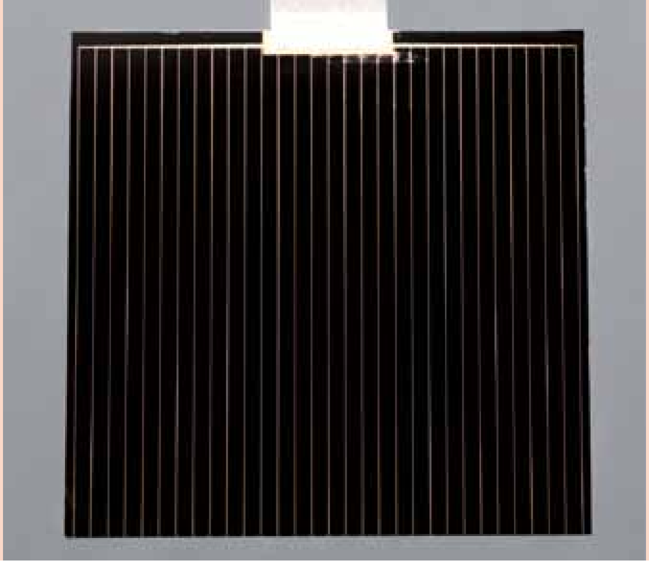
Fraunhofer ISE is working on the further development of epitaxial layer structures based on III-V semiconductor materials. At present we are intensively pursuing various research concepts to increase the efficiency of III-V multi-junction solar cells further. In addition to conventional triple-junction solar cells, further-reaching concepts such as quantum well solar cells, ultra-thin inverted structures and quadruple, quintuple and sextuple solar cells are being investigated and developed.

Armin Bösch, **Frank Dimroth**, Elvira Fehrenbacher, Jara Fernandez, Tobias Gandy, Wolfgang Guter, Harald Herrmann, Raymond Hoheisel, Peter Kailuweit, René Kellenbenz, Vera Klinger, Ranka Koch, Raymond Hoheisel, Eduard Oliva, Simon Philipps, Sebastian Rönsch, Michael Schachtner, Manuela Scheer, Gerald Siefer, Marc Steiner, Alexander Wekkeli, Elke Welser, Andreas Bett

1 A / B *Schematic representation of the current III-V research projects at Fraunhofer ISE. In addition to highly efficient triple-junction solar cells (A), further-reaching concepts such as quantum well solar cells, ultra-thin inverted structures and quadruple, quintuple and sextuple solar cells (B) are also being investigated and developed.*

The highest efficiency values that we have achieved for the conversion of sunlight into electricity have reached 41.1 % for triple-junction solar cells of III-V semiconductors. Sub-cells of the materials, GaInP, GaInAs and Ge, are used. These III-V multi-junction cells, that have been developed at Fraunhofer ISE, consist of up to 40 different layers, which are grown on top of each other by metal-organic vapour-phase epitaxy. At present we are pursuing various research concepts in order to improve the efficiency of multi-junction solar cells of III-V semiconductors still further (Fig. 1). The band-gap combination of lattice-matched triple-junction solar cells of $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ is not optimally adapted to the solar spectrum. Depending on the air mass, the solar cell is limited to varying degrees by the middle GaInAs cell. Introducing quantum wells into the space charge region of the middle cell shifts the current generation from the Ge sub-cell to the middle GaInAs cell. As a result, the efficiency of the whole triple-junction cell increases considerably. The first triple-junction solar cells with quantum wells developed at Fraunhofer ISE (Fig. 3) already display efficiency values of 27.1 % under AM0 irradiation.

A possible alternative to conventional triple-junction solar cells on Ge is presented by ultra-thin, inverted structures on GaAs substrates. In this case, for example, two inverted sub-cells of GaInP and GaAs are grown with lattice-matched crystalline structures and thus with few defects on GaAs, and then the lattice constant is enlarged to the third sub-cell of $Ga_{0.71}In_{0.29}As$. To achieve this, we are developing a transparent buffer of GaInP and transfer this "inverted" solar cell structure to a glass cover. We have designed and tested a new type of processing for these steps. The first solar cells, with a thickness of only 6 µm, have already been produced (Fig. 2).

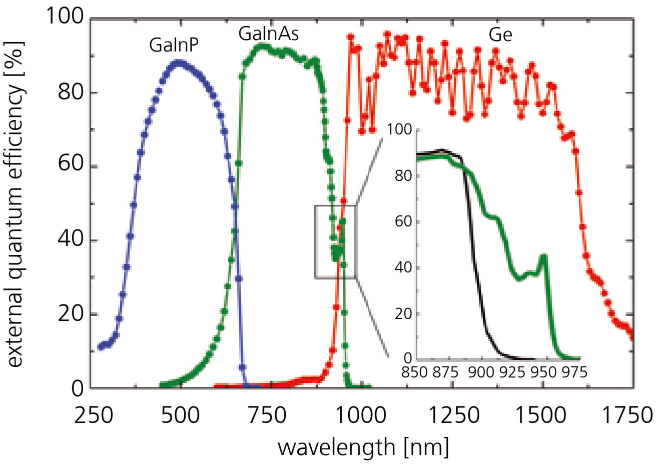


Due to the low mass, this technology is particularly interesting for space applications.

Solar cells with more than three pn junctions possess a still higher theoretical potential. At present, quadruple, quintuple and sextuple solar cells are being investigated at Fraunhofer ISE. Further III-V compound semiconductors such as AlGaInAs, AlGaInP and GaInNAs are needed for these concepts. These offer theoretical efficiency limits of up to 57 % in space (AM0) or 69 % in concentrator systems with a solar concentration of 500 (AM1.5d). At Fraunhofer ISE, we have achieved efficiency values up to 22 % (AM0) to date and open circuit voltages of 5.4 V. As the described structures are very complicated, in situ techniques for measurement during epitaxy are mandatory. This year, as part of an industrial project, we supported the development of an in-situ sensor further so that the curvature of the substrate can be measured in two independent directions. In this way, even the slightest stress can be detected during growth. In order to measure the IV characteristics of complex multi-junction solar cells correctly, we have set up a new measurement facility. With its six, independently adjustable light sources, this is the only solar simulator in the world where multiple solar cells with up to six sub-cells can be subjected to calibrated measurements.

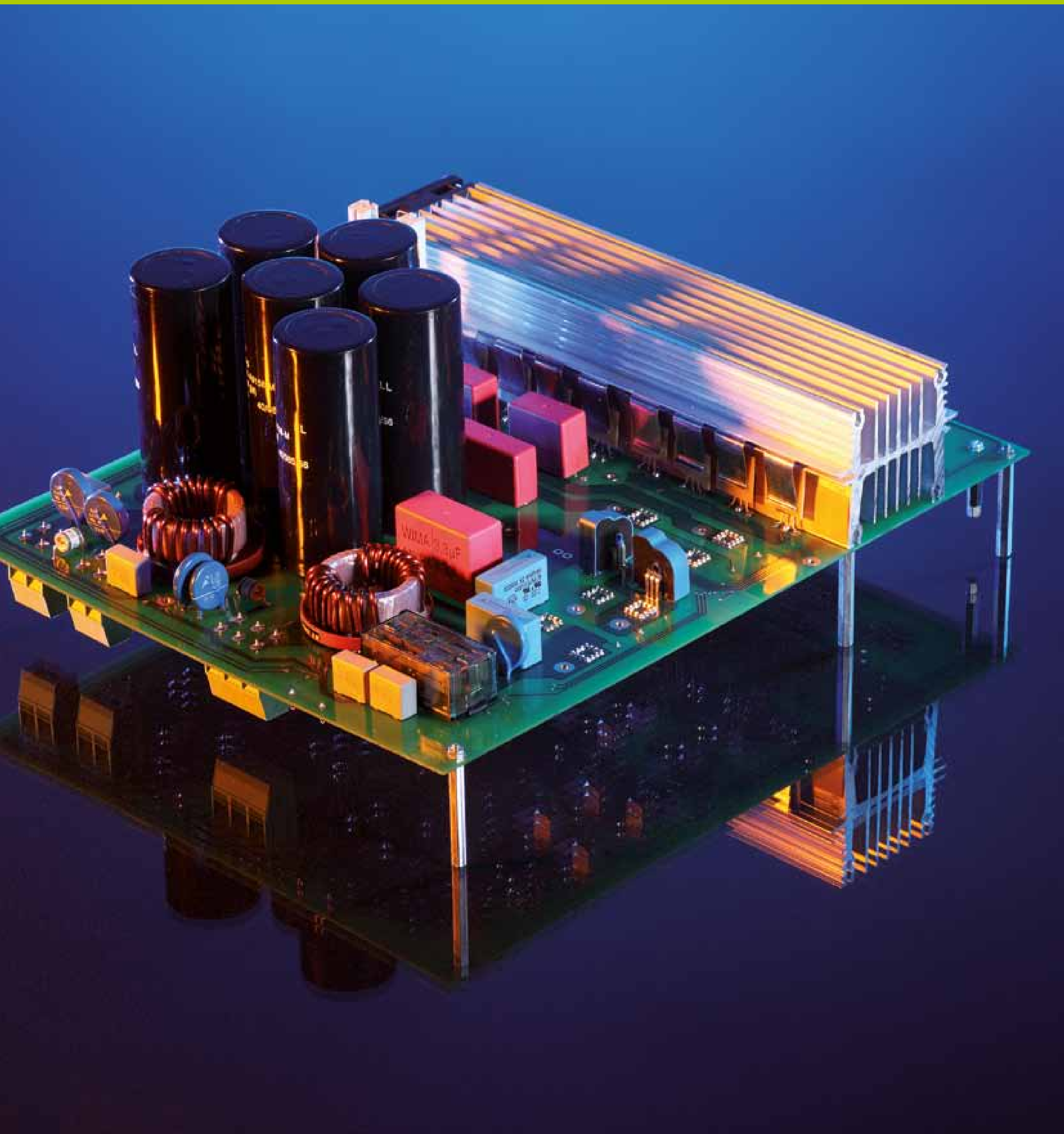
Our work was supported by the EU, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the German Federal Ministry of Education and Research (BMBF), the European Space Agency (ESA), the German National Aerospace Agency (DLR), the "Deutsche Bundesstiftung Umwelt" (DBU), the Reiner Lemoine Foundation (RLS) and the AZUR SPACE company.

2 *Ultra-thin cell with cover glass and cell connector. The cell weighs less than 40 mg cm^{-2} and is only 6 μm thin.*



3 *External quantum efficiency of a triple-junction solar cell with quantum wells in the GaInAs middle cell. In the insert, the extended absorption range of the middle GaInAs cell is clearly visible. For comparison, we have included the quantum efficiency of a standard middle GaInAs cell (in black).*

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. A good 10 % 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 are working intensively on optimising operation management strategies and control systems for all common types of technology in order to reduce battery aging and operating costs.

Construction of grid-connected systems is the largest global market of the photovoltaic branch today. To maintain the strong market growth stimulated by market introduction programmes now that subsidies are decreasing, the costs for the systems technology must be reduced continually. Inverters to feed photovoltaic electricity into the grid are already of high quality today. 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.

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) belong to the internationally leading laboratories in this field.

Regardless of whether photovoltaic, wind-energy, hydro-electric 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 electro-mobility, 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 industry, 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 more than 800 kW
- 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 measurement 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

In 2009, Fraunhofer ISE achieved an efficiency value of 99.03 % for photovoltaic inverters, topping its own previous world record. By using new components and improving the circuit technology, the researchers have thus achieved in decreasing losses by a further third compared to their earlier best performance. Junction field-effect transistors (JFET's) made of silicon carbide (SiC) from the SemiSouth company are now used. Furthermore, the transistor control and many other circuit details were optimised. The world record was measured on a complete PV inverter, including the power supply for inverter operation, a digital signal processor (DSP) for the controls, an LCL grid filter and a relay for grid connection.

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INTEGRATION OF ELECTRIC VEHICLES INTO THE ELECTRICITY GRIDS OF THE FUTURE

The Federal government is supporting the introduction of electromobility in Germany with a national development plan. Comprehensive charging infrastructure is needed to support this effort, which enables electric vehicles to be recharged and the consumed electricity to be billed. At the same time, the supply of energy to recharge the vehicles must be adapted to the fluctuating generation from renewable energy sources. We are thus developing charging units with integrated communications, Smart Meters and battery systems for electric vehicles.

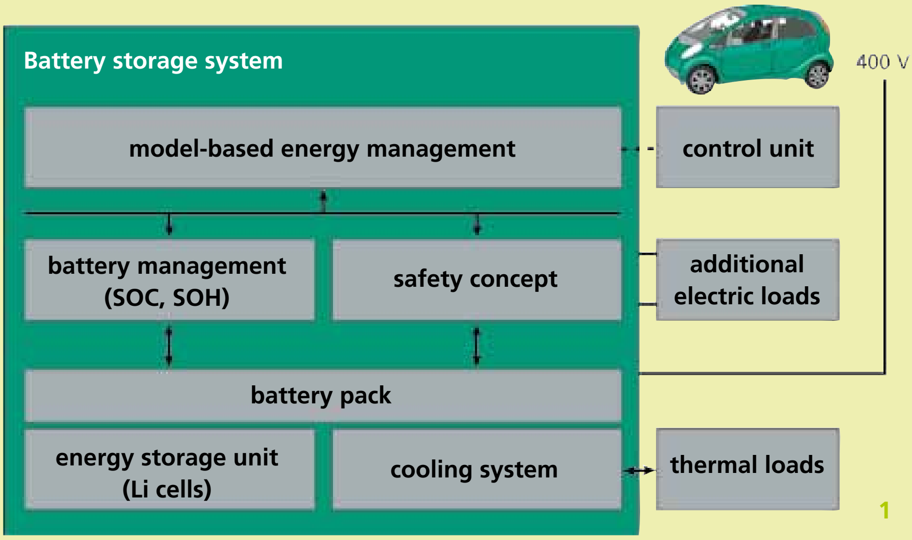
1 *Mobile Smart Meter, which was developed to implement communication, measurement and cost-accounting concepts.*

2 *The charging station for electric vehicles developed at Fraunhofer ISE, which e.g. provides information on the state of charge and optimises the charging time according to ecological and economic criteria.*

Rainer Becker, Bruno Burger, Timo Döscher, Frauke Heider, Daniel Herrman, **Robert Kohrs**, Jochen Link, Michael Mierau, **Dominik Noeren**, Norbert Pfanner, **Stefan Reichert**, Simon Schwunk, **Matthias Vetter**, Caspar Wiik, Christof Wittwer, Günther Ebert

The national development plan of the German Federal government for electromobility foresees a million electric vehicles on German roads in 2020. Only by using regenerative energy sources can these vehicles be operated with minimal emissions. As the availability of regenerative energy can fluctuate strongly, and simultaneous charging of many electric vehicles could cause considerable peak loads in the electricity grids, consumption and generation must be mutually adapted. By indirectly controlling the vehicle recharging with varying electricity tariffs for different times of the day, peak loads could be avoided and the energy supply for electric vehicles could be shifted to periods when there is a strong supply of regenerative energy. Furthermore, the batteries of the electric vehicles could support the electricity grid by feeding electricity into it during shortages. In addition to controlling the charging processes, it is necessary to determine the amount of energy needed by the electric vehicles. In order to offer special electromobility tariffs for vehicles, the electricity supply for households and for electric vehicles must be recorded separately. One option to achieve this is to establish infrastructure with one Smart Meter for a household and a mobile Smart Meter for use in an electric vehicle. The two Smart Meters can communicate with each other and exchange tariff data, registration data and quantities of energy.

The results of this work are also flowing into the project entitled "Fraunhofer Systems Research on Electromobility", which is supported by the German Federal Ministry for Education and Research (BMBF). Within this project, more than 30 Fraunhofer Institutes are conducting research on all the questions related to the development and introduction of electric vehicles. These include lightweight vehicle designs and engines, and also the charging infrastructure and grid integration of electric vehicles. Fraunhofer ISE is leading the sub-projects on battery system development and grid integration.



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INNOVATIVE BATTERY STORAGE SYSTEMS FOR ELECTROMOBILITY

Within the project "Fraunhofer Systems Research on Electromobility", we are co-operating with ten other Fraunhofer Institutes to develop innovative battery systems for use in purely electric vehicles and hybrid vehicles for local public transport. In addition to the project leadership, we are focussing on developing battery and energy management systems, on developing cooling concepts and on integrating individual modules and components into a functional and practicable battery system.

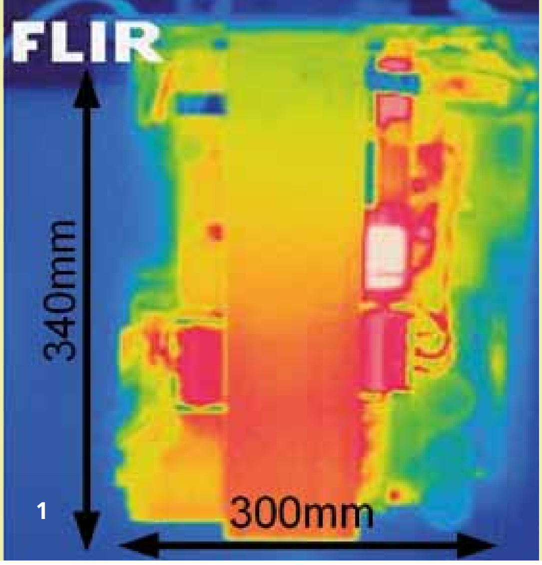
Stefan Gschwander, Max Jung, Stephan Lux, Simon Schwunk, **Matthias Vetter**, Günther Ebert

The pre-requisite to implement the vision of future sustainable mobility based on electric motors is a reliable, efficient and durable storage system. Lithium batteries, with their specific characteristics, particularly their high energy and power density and the long lifetimes that can be achieved, present a promising basis for such a system. We are thus co-operating with ten other Fraunhofer Institutes to develop battery systems based on lithium batteries which can be used as energy storage units in purely electric vehicles and hybrid vehicles for local public transport. Our work encompasses selecting suitable cells, testing to characterise the cells, designing the battery system, developing innovative cooling concepts integrating phase change materials, developing battery and energy management systems for optimised integration into the vehicle and integrating the individual battery modules and components to form functional and practicable battery systems.

The battery system for use in a purely electric vehicle has an energy content of 30 kWh and is able to drive two wheel-hub motors with a total power of 60 kW (continuous) and 120 kW (peak). The storage system for a hybrid local transport vehicle, an AutoTram® developed by Fraunhofer IVI, consists of lithium batteries with a storage capacity of 40 kWh to store energy and double-layer capacitors to provide power. The battery systems consist of individual modules, which in turn are composed of cells that are connected in series. Each module possesses its own battery management system, which is able to carry out battery diagnostics at the cell level and to communicate with a higher-level energy management system via a CAN bus (Controller Area Network). With this approach, problems can be recognised early at the cell level and countermeasures can be applied quickly, increasing the reliability and lifetime of the battery system.

1 *Battery storage system configuration (SOC = state of charge, SOH = state of health)*

2 *The energy management system determines the range and state of health of the battery system, controls the thermal cooling system, diagnoses fault conditions and controls the connected charging unit.*



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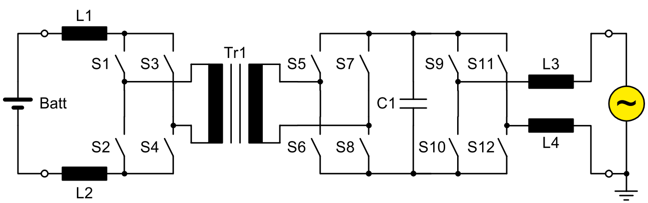
BI-DIRECTIONAL CHARGING UNITS FOR ELECTRIC VEHICLES

We are developing bi-directional charging units which are able to charge batteries and to feed electricity into the grid when required. The background is the increase in electricity generated from regenerative energy sources, in which fluctuating generation is confronted with a load which also fluctuates. As it will not be possible to control the future electricity grid without integrating further storage capacity, electric vehicles with their storage batteries will contribute significantly toward grid stabilisation.

1 *Thermograph of the bi-directional charging unit (without casing, with the heat sink in the centre). All inductive components, such as the AC and DC inductors, the HF transformer and EMC (electromagnetic compatibility) filters, are mounted together with the twelve power semiconductor components on the heat sink.*

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

Bi-directional charging units are being developed at Fraunhofer ISE in co-operation with industrial partners. Up to now, charging units have been designed for energy flow in a single direction. This means that only demand-side management is possible, i.e. time-shifting the consumed power. However, if the charging units are to support the grid actively by storing energy temporarily or providing grid services such as supplying reactive power, the charging unit must be able to control energy flows in two directions. A bi-directional, single-phase charging unit with 3.3 kW power was developed at Fraunhofer ISE as part of a fleet test of electric vehicles.



2 *Circuit topology of the single-phase, bi-directional on-board charging unit. The battery voltage range is between 200 V and 380 V.*

The vehicle manufacturers demand galvanic separation between the grid and the battery. This is implemented in the charging unit by a high-frequency (HF) transformer. The use of high switching frequencies results in a compact configuration for the entire unit. Despite the three-stage converter topology and the use of a transformer which increases the switching losses, a maximal efficiency value of > 93 % was achieved.

The aim of future work is to increase the power density while simultaneously raising the efficiency value. A trend toward higher charging power is foreseeable, which will allow the batteries to be recharged more quickly in future and thus make the electric vehicle more attractive for potential users. To achieve this, we are developing three-phase converter concepts. Experience from power electronics in the photovoltaic sector at Fraunhofer ISE can be transferred to electromobility and bring decisive advantages concerning questions of efficiency and grid integration.

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DEVELOPMENT OF CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES

Fraunhofer ISE is a significant participant in two fleet tests with electric vehicles, in which the everyday practicability of the vehicles and infrastructural solutions are being investigated. In the "Electromobility Fleet Test" and "Efficient Mobility" projects, we are focussing on the development and implementation of the complete charging infrastructure, with the goal of using electric vehicles exclusively on the basis of regenerative energy resources.

Rainer Becker, Bruno Burger, Jochen Link, **Dominik Noeren, Norbert Pfanner, Stefan Reichert**, Thies Stillahn, Matthias Vetter, Christof Wittwer, Günther Ebert

With its "National Electromobility Development Plan", the German Federal government is supporting the development and introduction of battery-assisted electric and plug-in hybrid vehicles. The goals are to reduce the emission of greenhouse gases and the consumption of fossil fuels, and to establish Germany as a leading market for electromobility over the next ten years. Fraunhofer ISE is contributing to the implementation of this goal within two fleet tests.

In the "Electromobility Fleet Test", we have been commissioned by the E.ON Energie AG utility together with Volkswagen AG to develop charging and communications infrastructure for plug-in hybrid vehicles, which is designed for operation with regenerative energy resources. The work encompasses the development of a mobile, intelligent meter in the vehicle, an intelligent socket, a rapid charging station, the complete communication solution between the vehicle, charging stations and central servers, and the development of a bi-directional on-board charging unit. The fleet test involves 20 vehicles and will run in Berlin and Wolfsburg.

1 *As part of the joint presentation of the "Efficient Mobility" project together with badenova, a demonstration version was shown of the charging station that we had developed for electric vehicles. This provides e.g. information on the state of charge and optimises the charging time according to ecological and economic aspects. The concept foresees both private and commercial use in future.*

2 *The electromobility of the future should be based on the most modern drive concepts and be implemented efficiently with renewable energy. The user should be able to use electricity from sun, wind and water for everyday driving – without restrictions compared to conventional vehicles. This is the goal of the "Electromobility Fleet Test" of Volkswagen AG and E.ON Energie AG, in which we have been sub-contracted to develop the entire charging infrastructure. The fleet test is supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU).*

In the "Efficient Mobility" project, which is supported by innovation funds from badenova AG & Co. KG, we are co-operating with the regional utility to analyse their fleet of 600 vehicles economically and ecologically. In addition to the utilisation ratio, primary energy aspects are being investigated, so that the potential to integrate electric vehicles with regenerative energy resources can be determined. A further research area is the load on the local electricity grid with a high penetration rate of electric vehicles in Freiburg. An intelligent, tariff-controlled charge management system is intended to prevent grid overloading and enable individual cost optimisation with CO_2-neutral charging from regional regenerative energy resources. The everyday practicality of the systems is to be demonstrated in a six-month field test.

RURAL ELECTRIFICATION: SUSTAINABLE PROGRAMMES IN SOUTH-EAST ASIA

The goal of the "RESIREA" project, which is co-financed by the EU, is to open up new markets for regenerative energy technology in South-East Asia. Together with our project partners, we are developing methods based on geographical information systems (GIS) to identify remote "electrifiable" areas and local resources. In addition to implementing microeconomic and technical programmes for rural electrification, we apply our methods and results to provide on-site training for local enterprises.

1 *A PV-hybrid stand-alone system in Laos.*

2 *Wood gatherer in Cambodia.*

Brisa Ortiz, Matthias Vetter, Günter Ebert

Biomass gasification systems, stand-alone PV systems and PV-hybrid systems to supply isolated grids are applied in Laos and Cambodia for rural electrification with renewable energy. The systems are used in villages which were identified with a geographical information system (GIS). These villages were selected on the basis of specific social and economic indicators, which resulted in a range from 123 to 2000 end consumers per village. In addition, the local conditions in each village differ, with the result that both the availability of renewable energy resources and the energy demand and general economic activities vary. In this context, 23 villages in Laos and 27 villages in Cambodia considered the use of off-grid power supplies to be extremely worthwhile. In order to identify a cost-covering technological solution, an economic and technical feasibility study was carried out. The provisional results showed e.g. that six of the nine villages, which had been selected as suitable for the implementation of appropriate technology, met the conditions for installing a gasification system. By contrast, the other three villages offered suitable boundary conditions for applying stand-alone PV-hybrid grids. Our efforts are directed toward developing an individual and "optimal system configuration" for supplying electricity based on PV systems for these settlements.

Fraunhofer ISE co-operates closely with European partners to promote the planning and implementation of national rural electrification programmes. Our activities aim particularly to stimulate the economic development of and local market for renewable energy technology.

RURAL ELECTRIFICATION: STAFF TRAINING

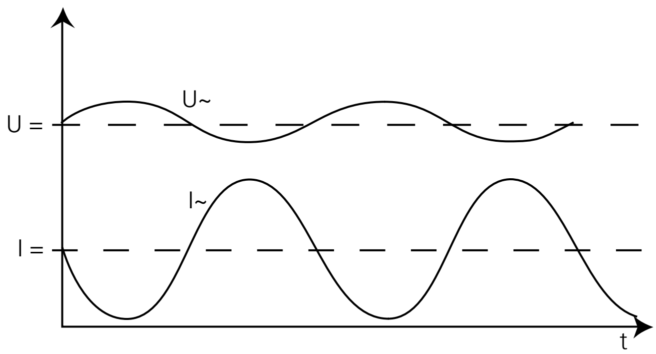
We train staff for companies, governmental agencies, research institutions and test laboratories in developing and threshold countries. The topics encompass the entire spectrum from the financing and introduction of rural electrification, through the technology and testing of system components, to the authorisation, operation and maintenance of the systems.

1 Training of a staff member from a Senegalese testing laboratory. Fraunhofer ISE established this testing laboratory ten years ago and offers comprehensive staff training on the testing of system components such as charge controllers, batteries and compact fluorescent lamps. This year, the testing facilities for PV modules, LED lamps and inverters were renovated and expanded.

Georg Bopp, Norbert Pfanner, Brisa Ortiz, Günther Ebert

Multi-facetted knowledge on rural electrification has been gained at Fraunhofer ISE over the past 20 years. In projects and special training seminars, we transfer this know-how to the staff of companies, governmental agencies, research institutions and test laboratories in the target countries, including Algeria, Cambodia, Ecuador, Ethiopia, Laos, Lebanon, Morocco, Pakistan, Peru, Senegal and Thailand. The topics range from the financing, introduction, technology and testing of system components to authorisation, monitoring, operation and maintenance of PV lamps, Solar Home Systems and central village power supply systems. Regarding system component testing, we provide advice on laboratory equipment and train staff in laboratories at Fraunhofer ISE or locally.

One focus is on the use of inexpensive and often simpler testing equipment, compared to the high-tech and usually more expensive equipment in our test laboratories. For example, when the efficiency value of inverters is measured in our laboratories, a very accurate and expensive power measurement instrument is used both for the input and the output signal. On the DC input side, one multimeter each for the voltage and the current can be used instead. As a large AC component is superimposed on the input current by the AC output current, a measurement error between 0.5 and 5 % results when the two DC values are multiplied to give the power. Many test technicians are not aware of this, as pure DC signals are usually assumed. The error can be simply corrected by measurement of the superimposed AC component. The training seminars were financed by the "Gesellschaft für Technische Zusammenarbeit" (GTZ), the EU, the "Stiftung Solarenergie" (Solar Energy Foundation) and in some cases, the countries involved.

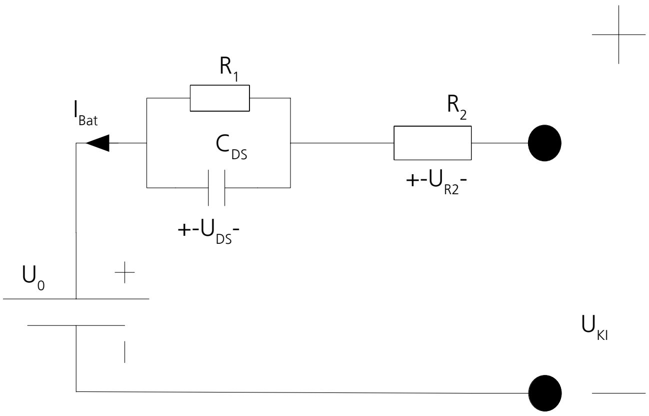


2 Current and voltage of an inverter on the DC side versus time. The superimposed AC component causes a measurement error between 0.5 and 5 % in the input power if the DC quantities are simply multiplied (arithmetic average). This error can be corrected by calculation if the phase shift between voltage and current and the AC component of each signal is measured. Correction with a simple approximation formula is adequate under most measurement conditions.

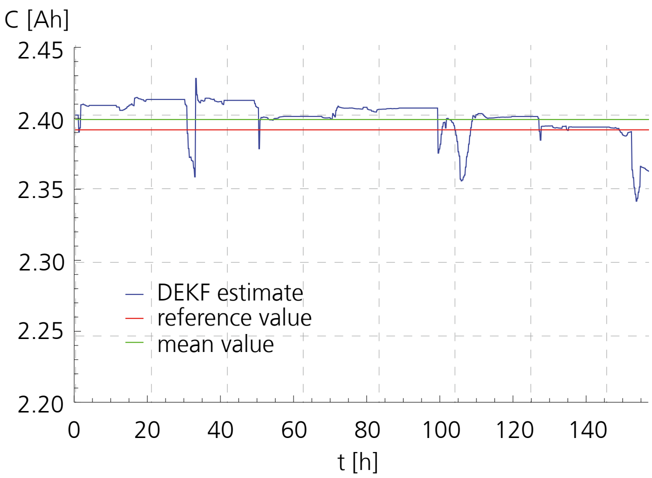
DETERMINING THE STATE OF CHARGE AND STATE OF HEALTH FOR LITHIUM-ION BATTERIES

It is important to determine the exact state of lithium-ion batteries to ensure their operating reliability and long lifetimes in large stationary and automotive applications. Applying model-based stochastic procedures, we are developing precise and robust methods for on-line determination of the state of charge and state of health of different types of lithium-ion batteries.

Nils Armbruster, Benjamin Knödler, **Simon Schwunk**, Matthias Vetter, Günther Ebert



1 *Lithium battery model to determine the state of charge. The open circuit voltage is modelled by a function, U_0, independent of the state of charge; the overvoltages resulting from current flow are represented by an RC circuit.*

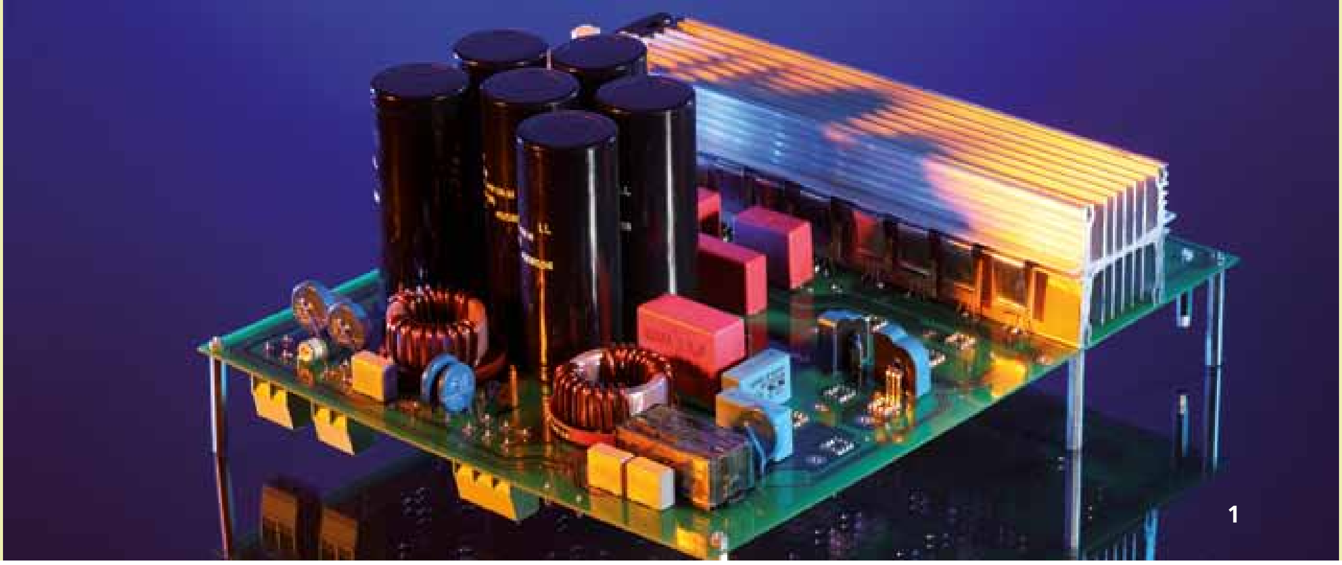


An inter-disciplinary approach is applied in developing algorithms to determine the state of charge with model-based stochastic methods: In addition to stochastic methodology and computer science to implement the algorithms, profound understanding of the battery plays a decisive role in developing the model approach. We apply Kalman filters in determining the state of charge, which optimally determine results calculated from two faulty models with well-known errors. This makes optimal and, most importantly, robust estimation possible even with noisy processes.

Figure 1 shows one of the models used. The dynamic behaviour of the battery is modelled by an RC component, which primarily reproduces slow diffusion effects in the battery. This allows the open circuit voltage, which clearly correlates with the state of charge in many types of lithium-ion batteries, to be determined even when current is flowing. The correlation is particularly clear if the cathode materials are based on manganese, cobalt and nickel. This model is combined with integration of the current, which is also determined from the state of charge. Depending on the state and type of battery, the model errors are adapted such that an optimal estimate of the state of charge is made.

We determine the state of health of a lithium-ion battery by combining the Kalman filter for determining the state of charge with a second Kalman filter to determine the state of health. The determination of the state of health is based on the assumption that the relationship between the open circuit voltage characteristic and the state of charge remains approximately constant. The result can be seen in Figure 2. The state of health as determined by the algorithm fluctuates within a narrow band around the true value; the average is very close to the true value. Altogether, relative accuracy of better than 1 percent is achieved in many applications.

2 *Determining the state of health of a lithium-ion battery. The remaining capacity of the battery, as determined with a Kalman filter, fluctuates within a narrow band around the capacity that had previously been determined in the laboratory. The average value is almost exactly equal to the true value.*



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HIGHEST EFFICIENCY VALUES FOR PV INVERTERS WITH SIC TRANSISTORS

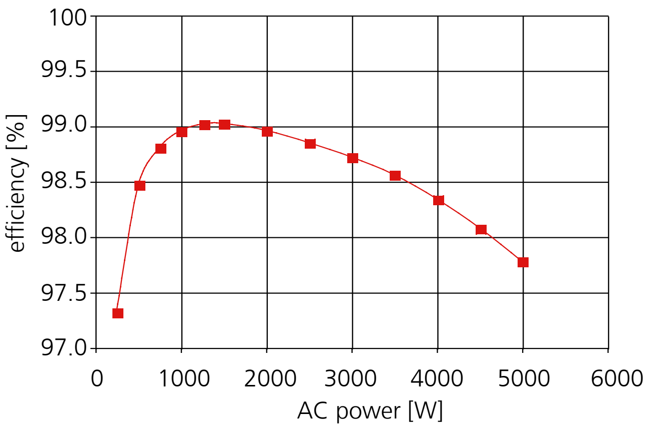
In our research on silicon carbide (SiC) transistors in inverters, we have not only achieved a major upward leap in the efficiency value but have also set new benchmarks for future developments. Many new opportunities are offered by the application of SiC transistors for us to continue developing PV inverters of the highest technical level for our clients.

Bruno Burger, Alexander Kaluza, Dirk Kranzer, Florian Reiners, Christian Wilhelm, Günther Ebert

The inverter is a central component of a PV system. The efficiency and reliability of the inverter have a strong influence on the system's return of investment. Inverters that have been developed at Fraunhofer ISE are distinguished by their high efficiency value and their technical maturity. Thus, it is clear that we continue to drive the development of inverter technology forward by the use of the newest technology – in this case by the application of SiC transistors. Transistors of SiC are clearly superior to the usual IGBT's of silicon (Si), particularly at higher voltages. Due to the material itself and the processing technology, transistors of silicon carbide are more expensive than equivalent transistors of silicon, such as are used today in PV inverters. However, it would be short-sighted to consider only the individual component costs. Instead, the cost advantages of the complete system must be taken into account. On the one hand, the use of SiC transistors offers the opportunity to increase the energy yields on a long-term basis due to the higher efficiency value, and thus to achieve higher income from feeding the electricity into the grid. On the other hand, the production costs for the inverter can be lowered by increasing the power density. The dimensions of the inductive components can be reduced by applying higher switching frequencies, for example. As a result of smaller system volumes and lower weight, the costs for warehouse storage, transport and installation can also be reduced. Figure 1 shows a single-phase PV inverter in the HERIC® topology, which was developed for the application of SiC transistors. Figure 2 shows the corresponding efficiency profile. To determine it, the complete inverter was measured and the parasitic consumption of the inverter itself was taken into account. An efficiency value exceeding 99 % and thus a new world record was achieved.

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

1 *Single-phase inverter in the HERIC® topology with normally-off SiC-JFET's. The switching frequency is 16 kHz. Due to our very good contacts to the leading manufacturers of SiC transistors, we have access to all transistor types that will become commercially available in future, and can name at least a second source for each transistor.*



2 *Efficiency profile for the single-phase inverter in the HERIC® topology for a DC voltage of 350 V. The maximal efficiency value exceeds 99 % today for the complete inverter, including its own parasitic consumption.*

CALLAB PV MODULES OCCUPIES A TOP POSITION IN A MEASUREMENT ROUND ROBIN

The revision, expansion and standardisation of procedures to characterise PV cells, modules and systems is the subject of the comprehensive "Performance" project. An important component of the work involves determining the accuracy of module measurement technology and improving it. Our work programme encompasses both crystalline silicon modules and various types of thin-film solar modules.

Daniela Dirnberger, Boris Farnung, **Klaus Kiefer**, Frank Neuberger, Christian Reise, Günther Ebert

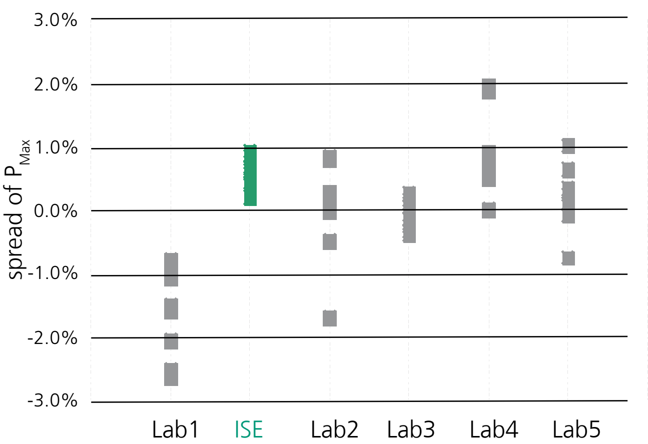
The various European measurement laboratories apply different types of measurement technology to determine PV module power accurately. The objective of one "Performance" sub-project is to quantify and minimise the differences in measurement results that are specific to individual laboratories or measurement technology. To this purpose, seven important measurement laboratories have carried out a series of steps in a work programme:

- registration of the instruments and measurement procedures used
- first round robin with ten c-Si modules and ten thin-film modules
- determination of the potential for improvement specific to each laboratory
- implementation of various measures for improvement
- second round robin with eight c-Si modules and ten thin-film modules

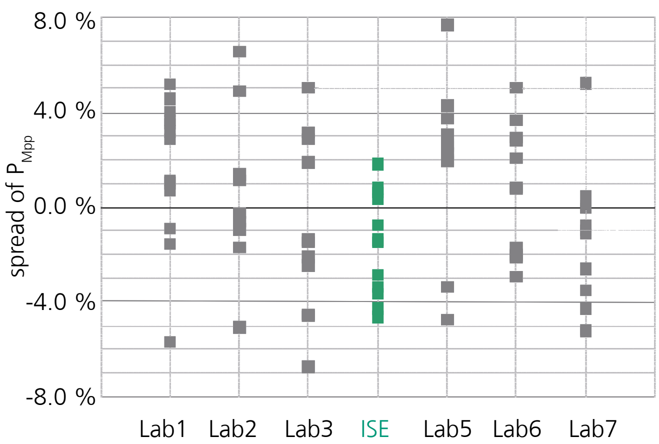
The first round robin already demonstrated the above-average quality of measurements at Fraunhofer ISE. Since then, we have further improved our accuracy by the use of matched reference cells, better reproduction of the standard spectrum by the flashlamp simulator and the application of professional laboratory equipment for measuring the dependence on irradiation and temperature.

In this way, Fraunhofer ISE was able to further improve its measurement accuracy compared to the first round robin, and thus to maintain its leading position. The improved accuracy, which is now referenced on a European basis, is available to all module manufacturers or system constructors.

The EU-funded "Performance" project is running for four years and is being carried out in close co-operation with the European Photovoltaic Industry Association (EPIA) as well as numerous individual companies.



1 *Results of the power measurement for a total of eight crystalline Si modules from four different manufacturers in the second round robin, with six European measurement laboratories participating.*



2 *Results of the power measurement for a total of ten thin-film modules from five different manufacturers in the first round robin, comparing seven European measurement laboratories. The second round robin had not been completed by the editorial deadline for this article, but improvements in the accuracy are also to be expected here.*

PV SYSTEM MONITORING: HOW GOOD ARE OUR YIELD PREDICTIONS?

Yield predictions are an essential tool for preparing financing concepts for larger photovoltaic systems. Scientific predictions can provide reliable information on the long-term average for the system yield within the specified tolerance. To guarantee the quality of our predictions, we regularly compare the predicted results with the measurement results obtained in our quality monitoring service.

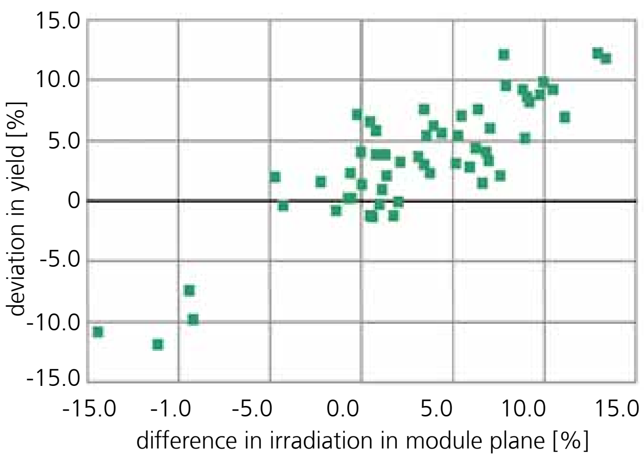
Wolfgang Heydenreich, Klaus Kiefer, **Björn Müller**, Christian Reise, Günther Ebert

The main information provided by a yield prediction is the anticipated annual energy yield as an absolute value in kWh or related to the system dimensions in kWh per kWp. Simulation models, which must reproduce the performance of the system components as accurately as possible, are used to calculate this predicted value. The uncertainty of these models, like the uncertainty in the meteorological data used, is taken into account in determining the total uncertainty for the prediction.

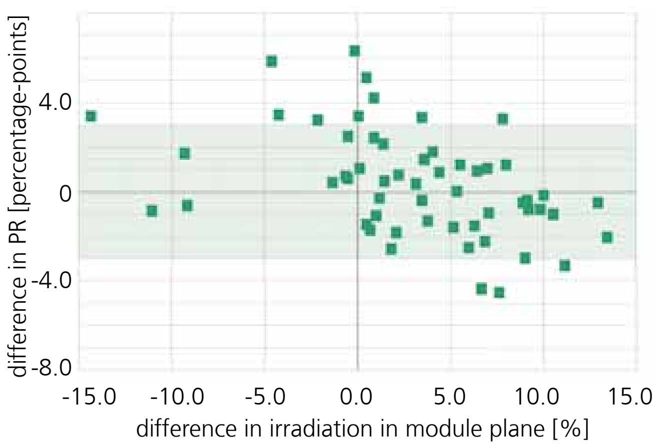
We were commissioned to provide not only the yield prediction but also the on-going monitoring for a number of commercial PV systems. This allows us to test the predicted values against the values measured in real system operation. Figure 1 shows this comparison for 33 PV power stations with a total power of 25 MWp for one to four years of operation.

The deviations in the annual yield primarily follow the deviations in the annual irradiation total from the values used for the prediction. The deviations in the performance ratio (PR), essentially characterising the uncertainty in our models, are largely independent of the deviations in the irradiation and amount to 0.7 percentage-points on average (Fig. 2). Deviations exceeding 3 % occur in only 13 of 56 years of system operation. We thus certainly meet our specifications for the simple standard deviation.

In all cases with larger deviations, we compared the assumptions for the prediction with the measured values in detail. The greater share of (positive) deviations can be explained by module power which was not correctly modelled. Our measurements for system authorisation and measurements in the module calibration laboratory indicate that in these cases, the supplied module power actually corresponds to the data sheet specifications or even exceeds it for some systems.



1 Deviation of the measured yields from the predicted values, plotted against the deviation between the measured and the predicted annual irradiation total. Each point represents one of 56 system operation years.



2 Deviation of the observed from the predicted values of performance ratio (PR). A correlation between the deviations and the difference in the annual irradiation totals is not evident here. High positive deviations are determined for some individual systems, which can be partly attributed to above-average actual module performance.

OPERATION MANAGEMENT OF CHP SYSTEMS IN THE CUXHAVEN E-ENERGY MODEL REGION

One main aspect of the "eTelligence" flagship project on E-Energy is access by combined heat and power (CHP) cogeneration plants to electricity trading on the regional market platform of Cuxhaven. Intelligent electrical-thermal operation management, which takes the thermal demand, local storage capacity and programmable loads into account, allows us to offer electricity products for trading on the market. To achieve this, we are implementing a standardised communications solution to connect all components.

Thomas Erge, Stefan Feuerhahn, Hermann Laukamp, Christof Wittwer, Michael Zillgith, Günther Ebert

1 *The eTelligence market place in Cuxhaven connects widely varying types of generators and consumers, such as households, commercial enterprises, public institutions and CHP operators. Even a virtual power plant and the regional grid operator, EWE NETZ, will trade on the market platform.*

Within the "eTelligence" project, we are focussing on decentralised CHP systems in the low to medium power range, which are increasingly feeding electricity from industrial and building-based plants into the electricity grid, and simultaneously provide space heating and process heat. We are developing solutions for intelligent energy management. Based on electric and thermal load and generation predictions, this allows the operation of CHP systems to be modified, so that in addition to meeting demands for heat, commercial electricity products and services can be offered on the eTelligence market platform. Such products include active power, reactive power, generation schedules or measures to improve the power quality. The core of our solution is an eTelligence gateway, in this case a decentralised embedded PC, which serves as a link between local system operation management and connection to the market platform. By using standardised communications interfaces and protocols such as the IEC 61850 or the Common Information Model (CIM), we guarantee inter-operability with the other participants in the eTelligence market place and transferability of the solutions for a later roll-out of the eTelligence concept. As an example, the "ahoi!" adventure baths company in Cuxhaven is participating in the market platform with its two CHP plants. In this case, we model the thermal demand profile of the baths and adapt the local SPS control systems to the specifications of the eTelligence market platform.

The project is being implemented by a consortium of six partners, EWE AG, BTC AG, energy & meteo systems, the Fraunhofer Energy Alliance, OFFIS and Öko-Institut, and is financially supported by the German Federal Ministry of Economics and Technology (BMWi).

DECENTRALISED ENERGY AND GRID MANAGEMENT WITH FLEXIBLE TARIFFS

An intelligent network of decentralised generators and loads offers significant potential for expanding the application of renewable energy sources. In addition to the opportunity to participate actively in the energy market and to reduce the cost of electricity, it will be possible to reduce the peak loads. At the same time, the demands on a grid management system and the required communications technology are high. For the first time, all Smart Grid functionalities will be implemented with the aid of an integrated Smart Metering concept that is co-ordinated by Fraunhofer ISE.

Rainer Becker, Stefan Feuerhahn, Robert Kohrs, **Christian Sauer**, Bernhard Wille-Haussmann, Christof Wittwer, Michael Zillgith, Günther Ebert

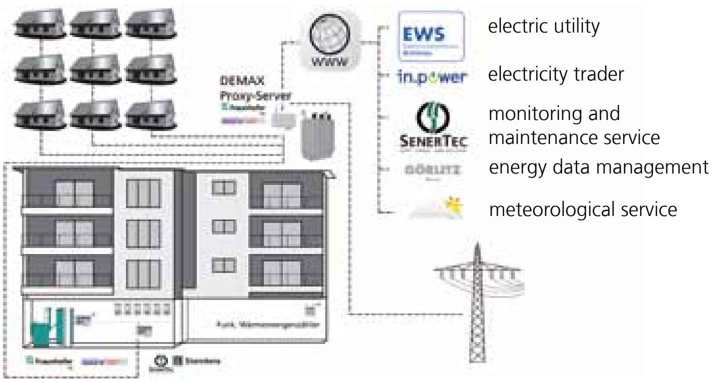
Within the InnoNet joint project, "DEMAX", an innovative energy management and communications system was developed, with which decentralised generators and loads from the commercial and private sector can participate in the energy market. The central component is an internet-based "embedded system" of the newest generation, which enables network-based communication via flexible media.

The concept: Numerous network connections for queries and responses by the systems are needed for distributed, interconnected energy systems in a Smart Grid. All communication for accounting, remote maintenance, process visualisation, etc. operates via an ordinary internet connection, without causing significant costs for data transfer. We have developed the standardised DEMAX gateway to connect the Smart Meters and the system components. The gateways are implemented in the local network with secure connections via a central proxy server to the service providers. In this way, all participating actors such as measurement services, electricity traders and grid operators can be linked via Internet connections with a back-up function. In practice, a higher-level virtual power plant operator can thus take over the control for generators and loads. Alternatively, indirect specifications arise as a result of variable tariffs.

The project partners are the Steinbeis Innovation Centre on "Embedded Design and Networking", the EWS electricity utility from Schönau, SSV Embedded Systems as a manufacturer of embedded hardware, Senertec as a CHP plant constructor, the in.power electricity and stock exchange trader and GÖRLITZ as a specialist for energy data acquisition.

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

1 *MUC gateway, which experts from Fraunhofer ISE have installed in the DEMAX demonstrator in Bad Bellingen.*



2 *Schematic diagram of the energy management and communications structure, with Smart Meters for electricity, gas and heat, DEMAX gateways, the central proxy server and networking of the participating service providers.*

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 that hydrogen will be used to store intermittently generated renewable energy, so that all desired energy services can 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 electric motors, serve in mobile applications as non-polluting engines for cars, trucks 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 obtain hydrogen and convert it efficiently to electricity and heat forms the core of the "Hydrogen Technology" business unit at Fraunhofer ISE. Together with our partners from science and industry, we develop components and complete fuel-cell 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, we are extending our portfolio to include 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 controlled 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 milliwatts to several hundred watts, 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 on-board electrical systems for cars, trucks, ships or aeroplanes (APUs), as well as stand-alone power supplies for off-grid applications and small portable electronic systems.

Spring contact pins to conduct electricity from a segmented fuel cell. Local losses, which are caused by an inhomogeneous gas distribution, kinetics and humidity, can be analysed with this specially developed cell in combination with a multi-channel impedance spectroscope. Appropriate changes to the configuration can be derived from this analysis. In combination with optimised operation management, this allows targeted improvement of the cell performance and lengthening of the lifetime.

CONTACTS

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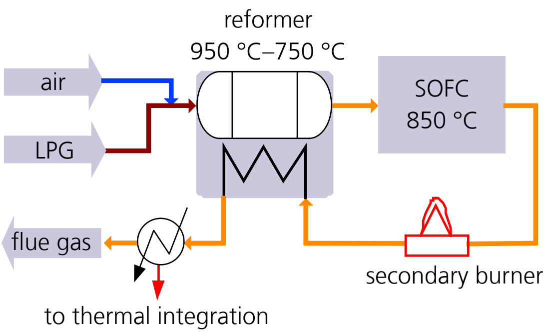
MINIATURE LPG REFORMER FOR A 100 W_{EL} SOFC SYSTEM AS A MOBILE POWER SUPPLY

For camping and leisure applications, we are developing a small LPG reformer as a fuel supply for a portable 100 W_{el} SOFC system. We use liquefied petroleum gas (LPG) as the fuel, as it features a high energy density and is available all over the world due to the very well established distribution infrastructure. The hydrogen-rich synthesis gas is produced by catalytic partial oxidation (CPOX), a reforming process which does not require any water.

Thomas Aicher, Gerard Kraaij, **Christoph Weuffen**, Christopher Hebling

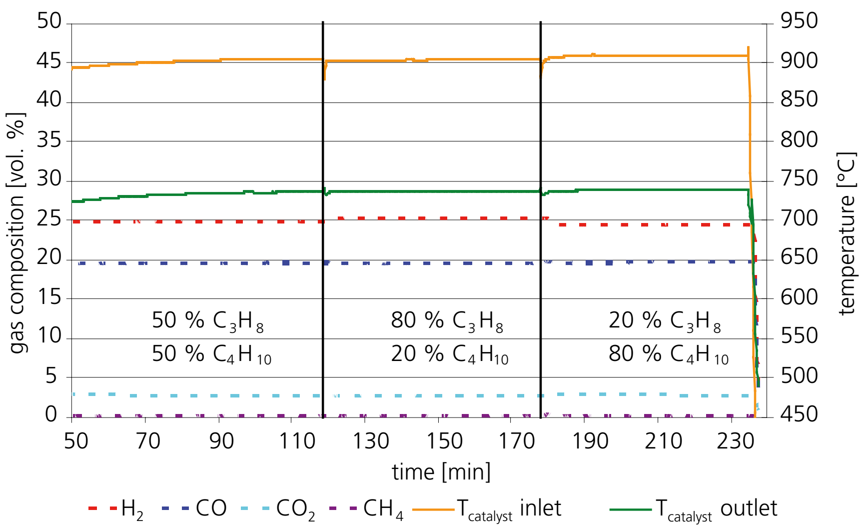


1 *Simplified flow diagram of the reformer/SOFC system. To reduce the thermal losses, the flue gas from the secondary burner is thermally coupled to the reformer. This means that the amount of air fed into the reformer can be reduced, which increases the yield of hydrogen and carbon monoxide.*

Catalytic partial oxidation (CPOX), a method to produce hydrogen from only fuel and air, is very attractive in combination with a high-temperature fuel cell, as this type of system does not require any further gas treatment. This combination is the basis for a simple, compact and portable power supply system for the low power range. Within a three-year internal Fraunhofer project, we are developing a reformer for such a system. Our work is concentrating on optimising the operating parameters and thermal integration.

We have achieved soot-free and stable operation of the reformer over a wide power range, from 25 to 100 % of the nominal power rating. In addition, we obtain gas temperatures of more than 750 °C at the reactor outlet, without exceeding the thermal limits of the catalyst. The results of sophisticated CFD simulation were applied in the design process to ensure that the products are well mixed, an important criterion to prevent hot spots and soot formation. In addition, the pressure losses were reduced and the reactor volume was decreased in the course of developing a series of prototypes.

During the final year of the project, investigations on long-term stability and the optimisation of start-up and shut-down procedures are planned. The work is funded as part of a Fraunhofer Foundation project and is being carried out in co-operation with Fraunhofer IKTS.



2 *Typical product gas composition for an air ratio of $\lambda = 0.38$. The relative shares of hydrogen and carbon monoxide (dashed red and blue lines, respectively) remain almost constant despite the varying mixing ratios of propane to butane.*

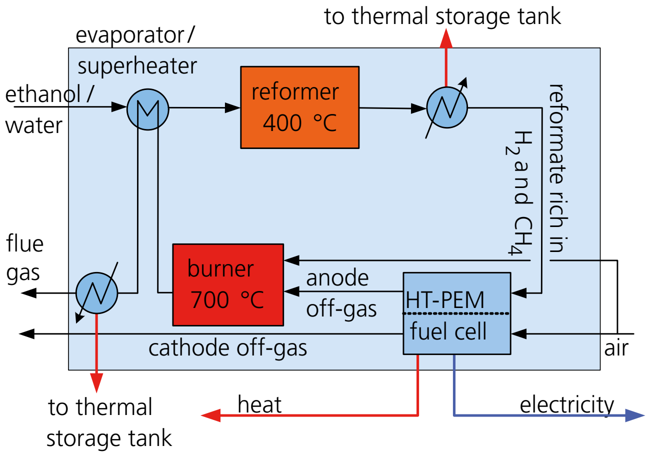
BIO-ETHANOL REFORMER WITH A HIGH-TEMPERATURE POLYMER-ELECTROLYTE-MEMBRANE FUEL CELL

In two test stands belonging to the Energy Technology Department, we have constructed a 6 kW_{th} combined heat and power plant that is based on a reformer/fuel cell combination fuelled with bio-ethanol. The power of 6 kW_{th} is sufficient to provide hot water, including that needed for space heating, to a house with a heat demand of 60 kWh/m²a. The generated electricity can either be used directly on site or be fed into the grid in accordance with the German Renewable Energy Law.

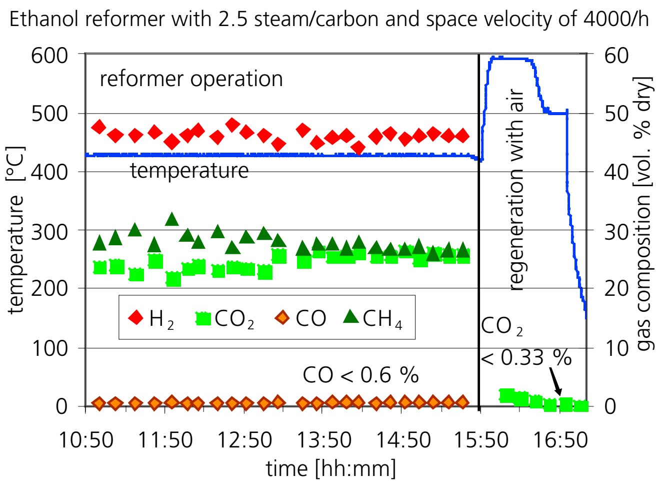
Thomas Aicher, Wolfgang Koch, Timo Kurz,
Lisbeth Rochlitz, Malte Schlüter, Christopher Hebling

Our innovative reformer/fuel cell system combines the advantages of the fuel cell, such as high efficiency values and low emission of noise or exhaust gases, with the advantages of bio-ethanol. The fuel is non-toxic, regenerative and commercially available throughout the world. The technology makes a significant contribution toward decentralising energy supplies and achieving CO_2 neutrality. The reformer system is designed as a household energy supply with a thermal power rating of 6 kW_{th}. In the test stand, we convert bio-ethanol into a hydrogen-rich reformate gas with the help of a catalyst at app. 400 °C. Due to its low CO content of < 1 vol. %, this reformate can be fed directly into a high-temperature PEM fuel cell with a temperature of 160 °C, which produces heat and electricity.

In contrast to conventional reformers, the system can be operated without gas purification. This makes it considerably simpler and more cost-effective. Furthermore, the required reforming temperatures are significantly lower, which saves energy to pre-heat the products. On the one hand, the fuel cell stack is operated in our HT-PEM fuel cell test rig with hydrogen, so that different operating conditions can be investigated in detail. On the other hand, the test stand is designed such that it can use the reformate gas produced by the reformer system directly. The anode off-gas from the PEM is then fed back to the burner of the reformer system. The burner is being developed by the TU Bergakademie Freiberg in co-operation with Promeos GmbH and burns both ethanol and anode off-gas. The generated heat is introduced via a highly integrated heat exchanger into the stratified storage tank of the SolvisMax® solar heating system manufactured by Solvis GmbH & Co. KG, thus minimising the thermal losses.

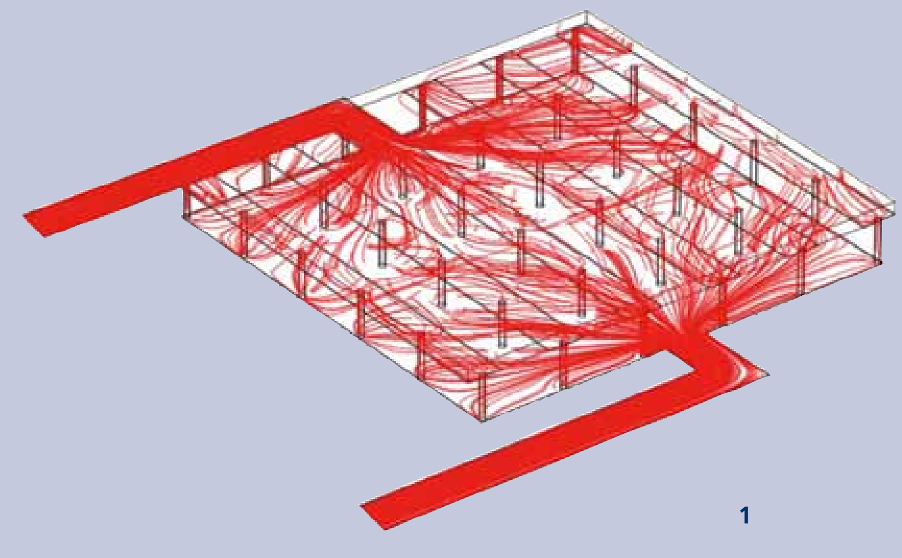


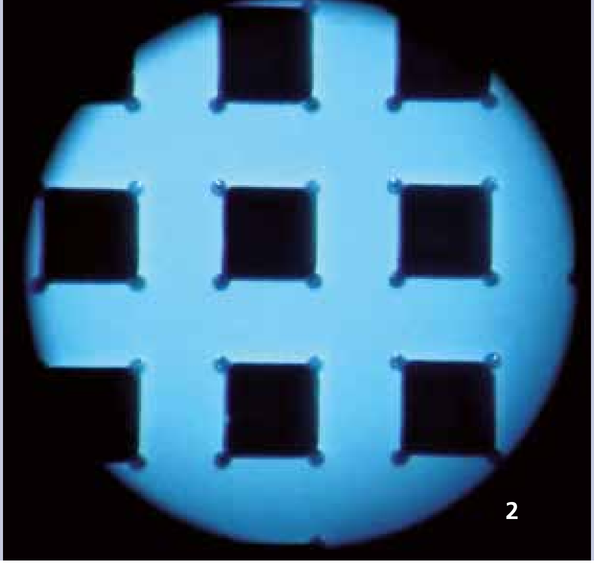
1 *Simplified flow diagram of the bio-ethanol reformer/fuel cell system designed as a household energy supply unit. The burner provides the heat of evaporation for ethanol and water. The heat from the flue gas, the reformate gas and the fuel cell is used to heat the domestic hot water tank. The calculated total system efficiency is 97.6 percent.*



2 *Measurement results from the reformer system: Starting with bio-ethanol and water, we produce a gas with 50 vol. % H_2 (dry), about 25 % each of CH_4 and CO_2, and less than 1 % CO. After several hours, we regenerated the catalyst with air, by burning away all of the soot deposits which had formed during the reforming process. This regeneration can also occur once or twice a day in a household unit without causing any problems.*

The work is funded by the German Federal Ministry of Economics and Technology (BMWi) within the "Renewable Heating Centre" project.





INNOVATIVE APPROACHES WITH MONO-ELECTROLYTE FUEL CELLS

In our newest generation of fuel cells, we have implemented an innovative construction principle in multi-layer ceramics. Significantly greater flexibility for the cell configuration is now possible than in conventional fuel cell stacks. The multi-layer ceramic technology offers a high degree of functional integration: Passive water management, electricity conduction and electric cell connection are achieved within the smallest possible volume.

Ulf Groos, Gerard Kraaij, **Mario Zedda**, Christopher Hebling

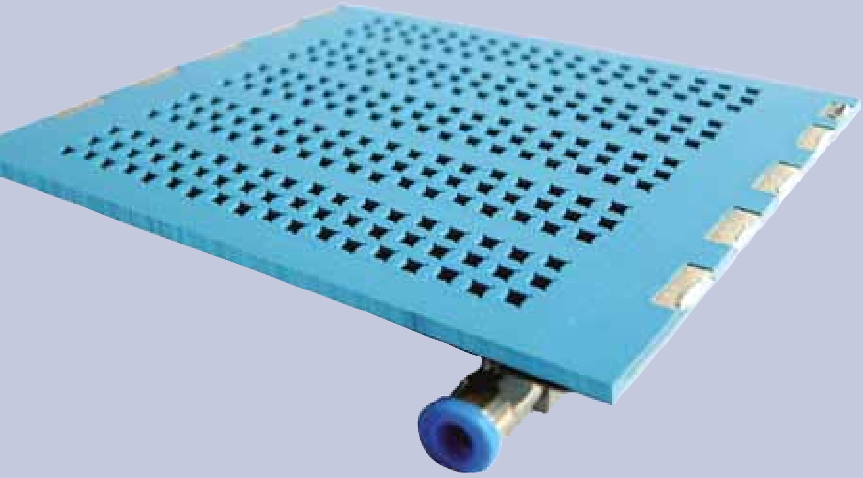
Multi-layer ceramic technology

We have developed a construction concept for our fuel cells which offers enormous geometrical adaptability to the application in question. We depart from the conventional stack configuration by locating and electrically connecting several cells in a single plane. If required, the cell planes can in turn be stacked. In this way, we are able to position the fuel cells three-dimensionally within a pre-defined volume.

Together with our project partner, Fraunhofer IKTS, we produce the flow field plates in multi-layer ceramic. The geometrical form is created by micro-perforation and laser-cutting. The high modulus of elasticity of the multi-layer ceramic guarantees excellent mechanical stability in the cell plane and thus the required clamping pressure.

1 *Simulation of the current conduction in a single fuel cell: If the voltage drop over the conducting layer is too large, the multi-layer ceramic technology offers a clever solution: Each of the extremely thin ceramic layers can be printed with electrically conductive coatings. The layers are connected in parallel with "vias" (vertical contacts through the stack with a diameter of only 0.2 mm).*

2 *Passive water management of fuel cells: Square cathode openings with an edge length of 0.5 mm and capillaries with 0.1 mm diameter at the corners of the squares. The product water from the fuel cell rises through the capillaries, while the reaction air can access the cathode unhindered.*



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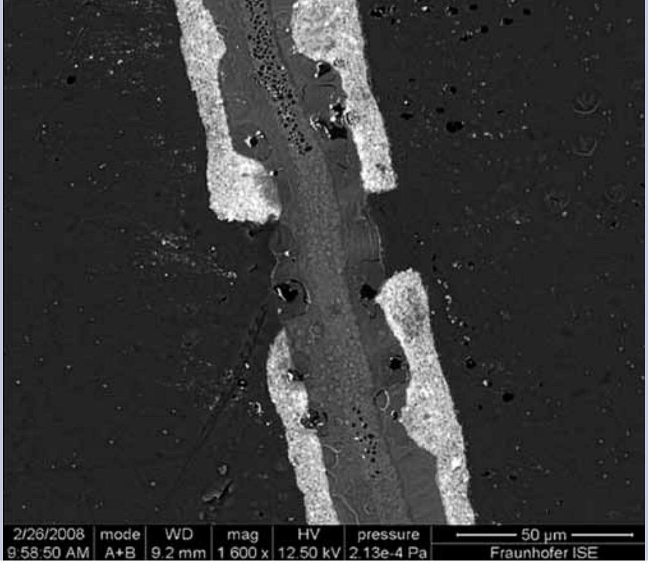


Mono-electrolyte configuration

Due to our "mono-electrolyte cell design", the assembly of a cell plane is not more complicated than that of a single cell in a conventional fuel cell stack. The cells in one plane "share" a common membrane-electrode assembly. The electrically conductive electrodes of the individual cells are insulated from each other by laser ablation, to prevent undesired leakage currents. The flow field plates, which are responsible for the gas supply, also correspond to those of a conventional fuel cell stack. All cells in one plane use the same flow field, which also offers the advantage that these do not need to be sealed individually.

Current conduction and cell connection

Multi-layer ceramic is an electrically insulating material. The current conductors for our fuel cells were deposited as 10 µm thin coatings by screen-printing on the ceramic. As a single coating does not have the required cross-section for low-loss conduction of electricity, we connect several layers in parallel. Electric "vias" with a diameter of 0.2 mm conduct the electricity through the 0.1 mm thin ceramic layers. The single cells are connected with each other in the same way.

Passive air supply

Small electric power supplies for portable appliances can be implemented with a single cell plane. We then open the cathode side of the individual cells to the surrounding air and thus enable purely passive ventilation without any support from fans or blowers. This benefits small fuel cell systems by improving their system efficiency. We have optimised these passive flow fields in measurement series and by simulation. The air supply, water removal, current conduction and mechanical stability are interdependent and have to be modified interactively.

3 *Fuel cell module in multi-layer ceramic technology: 5 cells, each with 8 cm² active area, are arranged within a single plane and connected in series. The module is supplied purely passively with oxygen from the surrounding air through openings in the housing. To achieve high output power values, the cell planes are stacked and a ventilator is used to supply the air.*

4 *Cross-sectional image of a membrane-electrode assembly that has been laser-segmented: The light layers are the electrodes that have been separated by laser ablation. In this way, undesired cross-currents between cells are prevented in the mono-electrolyte configuration. The membrane is optically transparent for the laser beam. The two electrodes can thus be segmented in a single processing step.*

Passive water management

By taking advantage of capillary effects, we are able to implement largely passive water transport. Suitable micro-channels and structures are produced by micro-perforation and laser-cutting in the multi-layer ceramic. The product water from the fuel cell is transported out of the flow field by micro-channels. Flooding is thus prevented and the reactants can reach the electrodes unhindered.

The project was supported by the Fraunhofer-Gesellschaft.

ONE ELECTRONIC SYSTEM FOR MANY FUEL CELLS

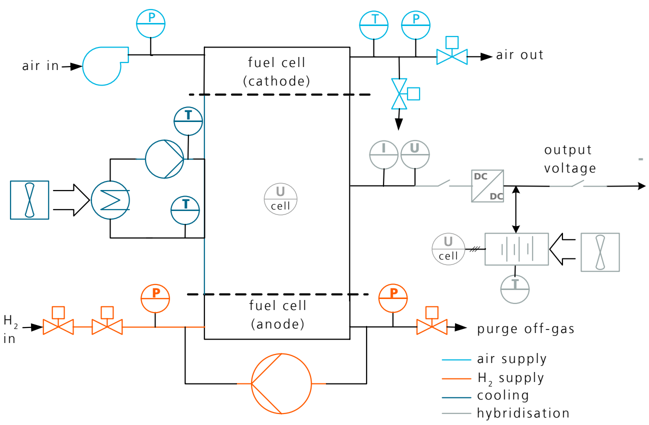
At Fraunhofer ISE, we develop control electronics for fuel cell systems with different system configurations, varying the power range, fuel or ambient conditions. In addition to the circuit design, we implement a flexible software concept which can be adapted to the various fuel cell systems. The combination of a fuel cell with a rechargeable battery is also integrated into the software architecture, so that many different application cases can be designed accurately.

Ulf Groos, **Stefan Keller**, Christopher Hebling

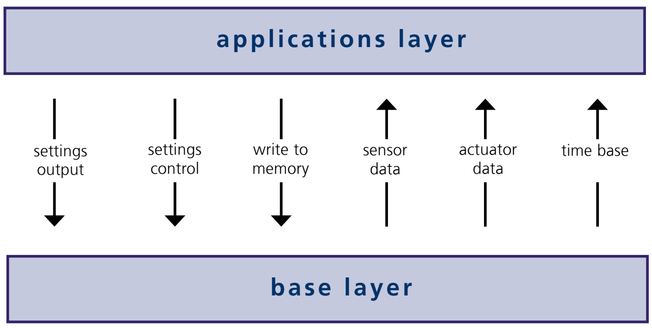
In order to develop universally applicable control electronics for fuel cell systems, we initially analysed the constellations of systems in the power range from 20 to 2000 W_{el}.

This allowed us to estimate the number and structure of controls needed for actuators such as pumps, valves, fans, etc. and for sensors. In the next step, suitable commercially available electronic components were identified and their connections were designed. We did this in close co-operation with our project partner, MAGNUM Automatisierungs-technik GmbH. The main criteria were minimal electricity consumption, low space requirements and low costs, while still retaining the greatest possible flexibility. For instance, the electronics can process any choice of sensor voltage and is designed to operate with inexpensive thermistors to determine temperatures. The output steps for the actuators can be scaled and provide either a pulsewidth-modulated or an analog control signal, as well as modulation of the supply voltages for the actuators. This allows various components to be integrated quickly to implement a fuel cell system.

A digital micro-controller is the central electronic component. It is connected to the hardware via standardised digital interfaces, so that it can be designed to provide powerful computing resources or to save energy, as required by the system at hand. In addition, we are developing a software concept which can be simply adapted to the different fuel cell systems. As well as providing control functions for the sensors and actuators, the software includes fundamental operation management of the fuel cell system and offers the option to integrate a rechargeable battery as a buffer.



1 *Schematic diagram of a water-cooled fuel cell system: Our electronics controls all of the system actuators and reads values from all the sensors. Furthermore, it can interact with sub-systems such as smart batteries, charge controllers or AC converters. In addition, it offers data logger functions and data transfer to a PC.*



2 *Implementation layers within the electronics software: The applications layer includes the operation management and other functions which do not depend critically on time. All functions immediately affecting the hardware are implemented in the separately encapsulated base layer. In this way, we achieve high operating reliability. At the same time, it is possible to integrate applications software from other systems.*

BIOMASS GASIFICATION TO GENERATE TAR-FREE SYNTHESIS GAS

In the Energy Technology Department, we have constructed a biomass gasifier on a technical prototype scale for a thermal fuel power rating of 50 kW. Initially, we are investigating wood pellets, but later other types of biomass are planned, e.g. pruning off-cuts. We aim to demonstrate that the innovations that are protected in the Fraunhofer ISE patent, DE 10 2004 024 672 B4, can be technically implemented to produce a tar-free synthesis gas, not only on a laboratory scale. With our process, gas scrubbing after the gasifier is no longer needed.

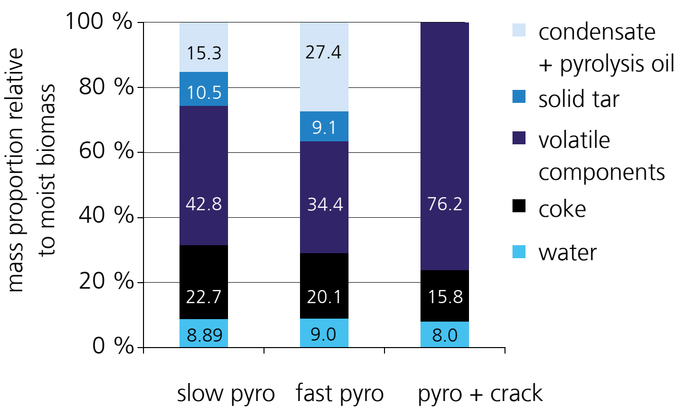
Thomas Aicher, Luisa Burhenne, Christian Lintner, **Lisbeth Rochlitz**, Malte Schlüter, Christopher Hebling

Decentralised systems to gasify biomass in the power range below 1 MW are well suited as an autonomous heat and power supply, also as a complement to weather-dependent renewable sources of energy such as the sun and the wind.

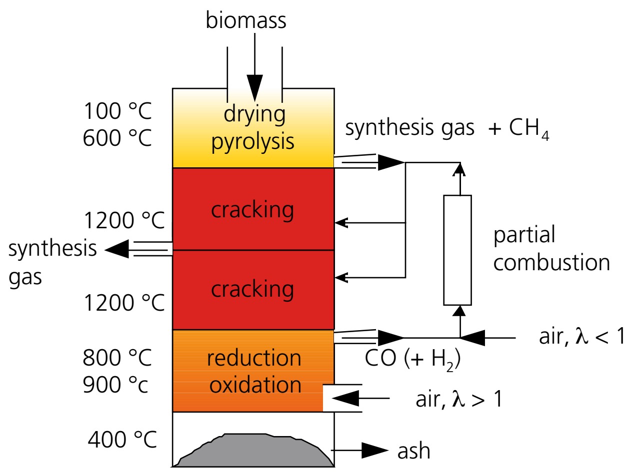
We have investigated the reaction steps of pyrolysis and gasification (cracking step) of biomass in laboratory experiments with two reactor stages connected in series. Woodchips were pyrolysed with N_2 at up to 600 °C and subsequently gasified in a second reactor. We added simulated synthesis gas as well. In the laboratory, we were able to demonstrate thermal and autocatalytic cracking of the tars which were produced by pyrolysis. Tars are undesired by-products of gasification which negatively affect the functionality of subsequent components, particularly engines. The experiments proved the technical feasibility of our innovative procedure.

Without the need for gas scrubbing, our procedure produces a product gas with a tar content of < 50 mg/m^3, whereby the loss on ignition of the ash is < 5 %. We achieve this by controllable, external, partial combustion of gases from the pyrolysis and redox zones (see Fig. 2). The hot product gases create significantly higher temperatures in the cracking zone than other solid-bed gasifiers, which is positive for the tar conversion. By applying robust, well-proven technology, high reliability and economic viability should be achieved for the gasifier. We generate electricity and heat from the produced gas in a gas-fuelled combined heat and power plant. Overall, an efficiency value exceeding 95 % is targeted (generated electricity and generated heat relative to the initial thermal energy content of the fuel). This is a significant increase compared to existing systems.

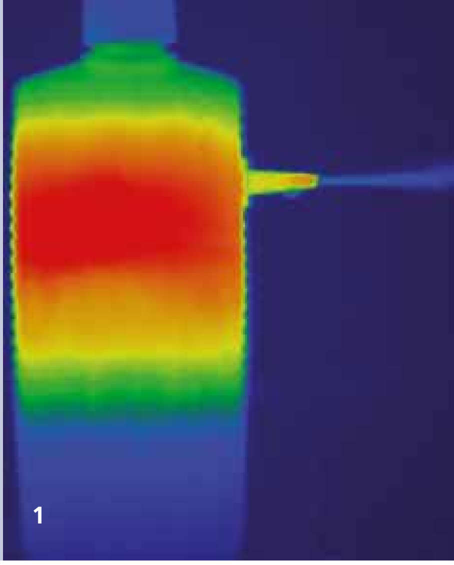
The project was funded by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) as part of its initiative against climate change.

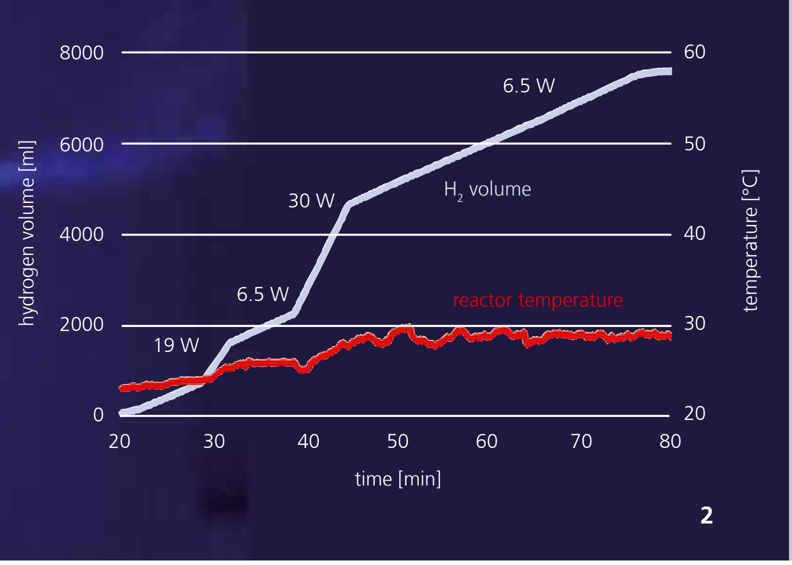


1 Comparison of product proportions from laboratory experiments. Left: Slow pyrolysis (heating rate app. 5 K/min.), centre: Fast pyrolysis (app. 60 K/min.), right: Pyrolysis with subsequent thermal and autocatalytic cracking of tars and pyrolysis oils at 900 °C, without addition of a gasifying agent. The product no longer contains any condensable tars.



2 Biomass gasifier with innovative gas distribution and external partial combustion to increase the temperature in a controlled way during the cracking step. By dividing the gas flow after the partial combustion, the pressure loss in the cracking step is minimised, while the time which the product gases remain in the chamber is simultaneously increased. This means that the tars can be cracked efficiently. The redox zone ensures that the biomass is completely combusted, so that high gasification efficiency is achieved.





ALTERNATIVE HYDROGEN SOURCE FOR PORTABLE FUEL CELL SYSTEMS

We are currently developing a hydrogen generator based on low-molecular, hydrogen-rich chemical compounds. By carefully selecting the materials used in the storage system, we are able to provide high-density hydrogen storage at atmospheric pressure. With appropriately adapted system concepts, we are aiming to supply PEM fuel cells with extremely pure hydrogen.

Parag Deshpande, Wolfgang Koch, **Johannes Kostka**, Tom Smolinka, Christopher Hebling

Fuel cells are particularly advantageous in combination with fuels of high energy density, which can also be easily stored and transported. One main focus of our research is thus to provide a hydrogen supply for PEM fuel cells based on chemical compounds that meet these requirements.

Together with our partners, we are currently developing an autonomous miniature energy system for applications in a power range up to 100 W_{el}. The hydrogen-generating unit of the system applies an innovative process to generate and store the hydrogen with chemical hydrides.

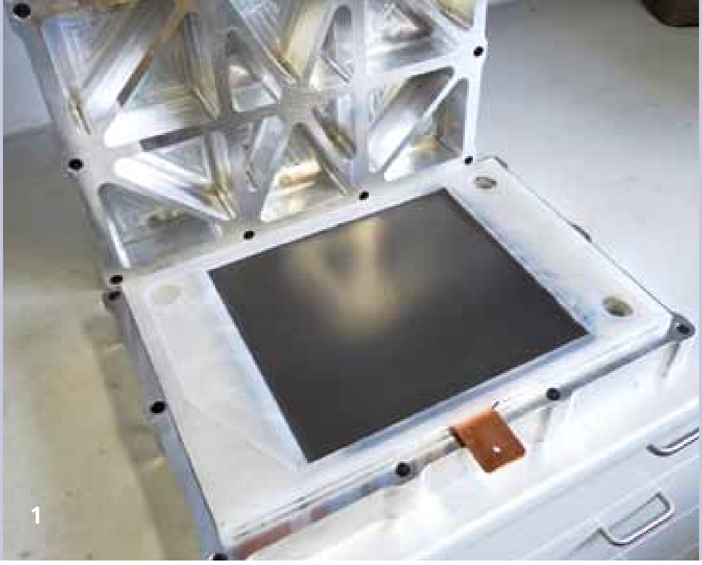
With the support of the TU in Freiberg and the Chemetall GmbH company, we developed a special storage solution, which is resistant to flames and heat, and features extremely low application temperatures down to -40 °C. With the help of the generator system, which was also newly developed, about 5 wt.-% of extremely pure hydrogen can be released from the storage solution.

1 *The infrared image of a hydrogen reactor shows the temperature distribution during operation. The dark red zones correspond to temperatures of about 80 °C. The hydrogen generated at the time when the image was recorded was sufficient to operate a 70 W_{el} fuel cell system.*

2 *By accurately transporting the storage solution into the reactor, it is possible to control the demand for extremely pure hydrogen in a fuel cell quickly and exactly. Figure 1 shows the hydrogen release characteristic from one of our generator developments for fuel cell systems with an output power of up to 30 W_{el}.*

In order to achieve the highest possible energy density for the complete system, we are pursuing a minimalistic system approach: We achieve control over the complex reactions for hydrogen release by adapted reactor geometry and distribution systems, which we are presently developing with our partners from DMT GmbH. Attention is also being given to the application of lightweight and inexpensive polymer materials.

Drawing on our long years of experience in the hydrogen-generation field, we are able to design cost-effective systems which will be able to contribute toward meeting the high energy demands of off-grid and portable applications in future. The work is supported by the German Federal Ministry of Education and Research (BMBF).



VANADIUM REDOX-FLOW BATTERIES FOR DECENTRALISED APPLICATIONS

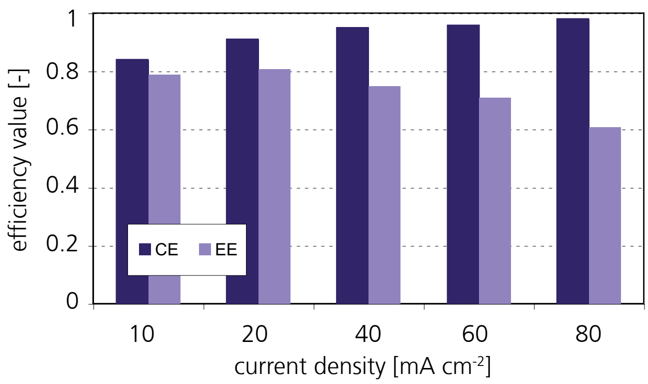
Due to the large proportion of energy generation from renewable – and thus often strongly fluctuating – sources, energy storage plays a decisive role in decoupling demand and supply. Redox-flow batteries feature major advantages, particularly in decentralised applications such as island grids and mini-grids. For this reason, we at Fraunhofer ISE are intensively pursuing the development of stacks and systems, as well as battery management for this electrochemical form of storage.

Martin Dennenmoser, Daniel Frick, Peter Gesikiewicz, Beatrice Hacker, **Tom Smolinka**, Matthias Vetter, Felix Waldkirch, Christopher Hebling

Redox-flow batteries store electricity in a chemically bound state in the active mass of liquid electrolytes, which are stored in separate tanks for the positive and negative sides. For energy conversion, the electrolytes are pumped through the electrochemical cell, so that the active ions of the electrolytes can be charged or discharged. The central component of a redox-flow battery is thus the cell stack, which serves as the electrochemical conversion unit. Within the internal Fraunhofer research project on "Advanced Energy Storage", we are developing optimised cell stacks at the Institute for application in small, isolated grids (individual houses, stand-alone island grids) or also grid-connected storage systems in connection with electricity generators converting renewable energy. Our tasks include cell design, fluid dynamics, sealing concepts and electrolyte supply. Furthermore, the cell stack design must be suitable for manufacturing in large numbers.

We screen materials for the electrodes, membranes and bipolar plates to optimise the electric operating performance of the converter. Figure 1 shows a cell stack of 18 cells with

1 Layout of a 700 cm² cell stack, consisting of 18 cells with a nominal power of 1 kW.



2 Coulombic and energy-relevant efficiency values (CE and EE) of a 250 cm² multi-cell stack (five cells) as a function of the current density. The efficiency values have been determined for charge/discharge cycles (IU charging and I discharging) between 2 % and 98 % state of charge (SOC).

a total active surface area of 700 cm², which supplies power of about 1 kW. Figure 2 shows the measured coulombic and energy-related efficiency values for a multi-cell stack as a function of the current density. At the cell level, cycling efficiency values of 70 to 80 % can be achieved.

Starting from these measurements, in parallel we develop model-based control strategies, which allow optimal operation of the redox-flow battery system with respect to energy consumption. To this purpose, a component system model for a redox-flow battery is set up in the Dymola simulation environment, with which we can investigate control strategies and algorithms.

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 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 and a battery testing 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 by DAP (Deutsches Akkreditierungssystem Prüfwesen GmbH) 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 a tracker
- indoor test stand with a solar simulator (max. aperture area 3 m x 3.5 m)
- 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 2009 and now offers an even wider range of possibilities for co-operation (see article on p. 118 ff).

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. 112 ff).

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. The capacity and available space are being expanded continuously. The goal of the facility is to ensure the quality and reliability of PV modules, which is becoming an increasingly important issue. Within the framework of its co-operation with the VDE Institute, Fraunhofer ISE is responsible for the relevant performance tests, while the VDE Institute carries out the safety tests and certification according to the usual standards. 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 is closely linked with the calibration laboratory at

Fraunhofer ISE, comprising CalLab PV Cells and CalLab PV Modules. Similarly, TestLab PV Modules co-operates with module producers (see article on p. 110).

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 solar cells and modules plays an important role in product comparisons and for quality assurance of PV systems. 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 page 114 ff).

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 automobile applications. We carry out electrical and thermal characterisation and aging tests.

Fraunhofer ISE has operated an indoor collector test stand with a solar simulator since 2002. Its excellent reproducibility allows targeted development of collector constructions to be carried out very efficiently. TestLab Solar Thermal Systems is completely accredited to carry out all measurements specified by DIN EN 12975-1,2:2006.

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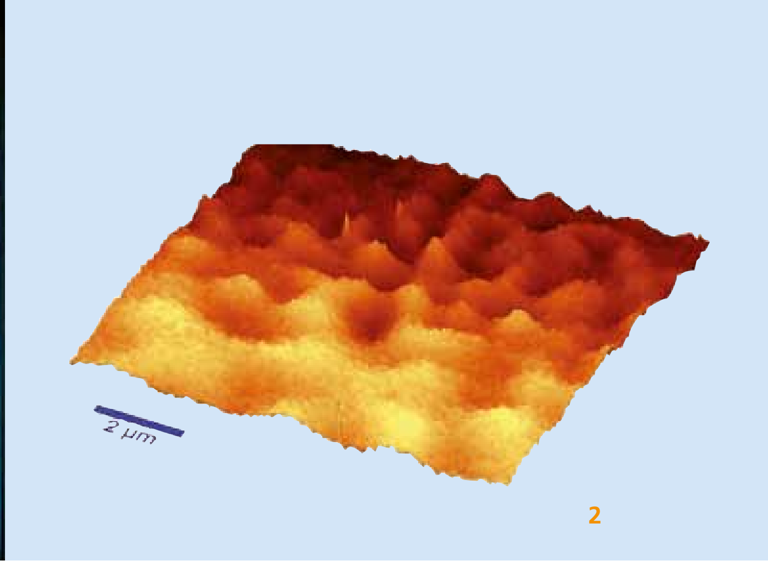


EXPANDED CAPACITY TO TEST PV MODULES

After commissioning the new rooms for "TestLab PV Modules" in September 2008, the staff and equipment capacity was further expanded in 2009. The newest test facilities are now available for testing PV modules according to IEC 61215 and 61646. This means that the time for testing has been reduced significantly.

Holger Ambrosi, Stefan Brachmann, Ilie Cretu, Jürgen Disch, **Claudio Ferrara**, Jakob Grimm, Markus Heck, Michael Köhl, Kerstin Körner-Ruf, Marcus Larisch, Georg Mülhöfer, Daniel Philip

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 *False-colour images from Raman microscopy of a PV module with ethyl vinyl acetate (EVA) as the encapsulation material. Intensity profile of the CH valence vibrations in the EVA over an area of 10 µm x 10 µm.*

New testing facilities, both those developed at Fraunhofer ISE and those acquired commercially, make both faster IEC-based tests and tests according to clients' specifications feasible.

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 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. Alternatively, light-soaking can occur on our extended outdoor test stands. In both cases, the output power, the radiation intensity and the module temperature are monitored continuously and the characteristic IV curves are measured several times per hour.

To investigate damage to modules, non-destructive methods are used at the TestLab PV Modules, including electroluminescence (on entire modules) to detect damage to cells or cell connectors, and optical and Raman spectroscopy (Fig. 2) for the encapsulation materials.

QUALITY ASSURANCE OF PV POWER PLANTS

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 in order to guarantee the best possible quality of a system throughout its operating life.

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

Yield prediction

A reliable yield prediction can be made only when the site is taken into account with its specific boundary conditions. After determining all relevant data, we carry out a scientific yield analysis. In addition, we provide information on the following points:

- Error analysis – How accurate are the results?
- Risk analysis – What factors could reduce the yield?
- Performance Ratio – How good is the system efficiency of the planned system?
- Evaluation of the system technology – How good are the components and their dimensioning?
- Reliability indicators – How can initial controls, authorisation measurements and monitoring additionally help to ensure that the predicted yield is obtained?

Recent comparison of our predictions with the monitored results showed very good agreement, which is within the specified tolerance.

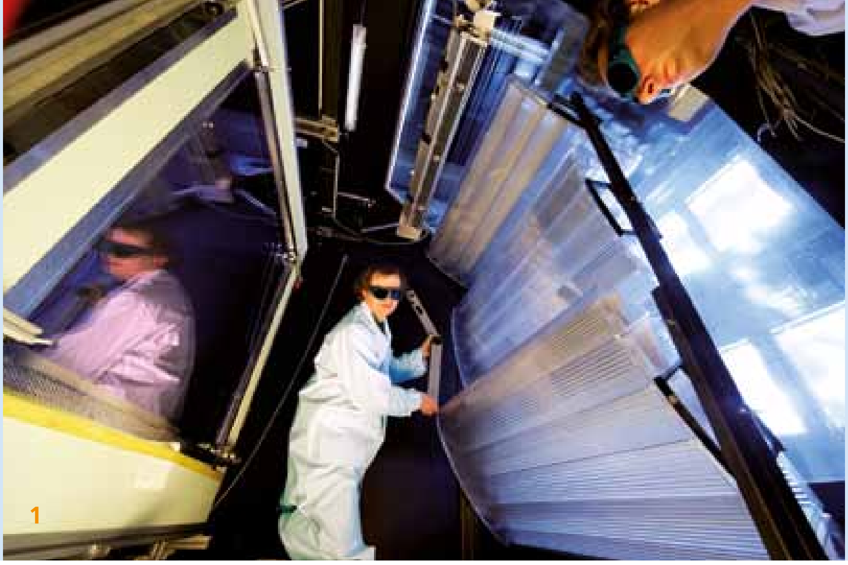
System testing

Measurement of the system power, testing of the system functionality, determination of possible weaknesses and testing compliance with technical standards are the main points of a comprehensive procedure on site. Faulty modules and defects in the generator circuit can be identified with our mobile measurement equipment. The results are documented in a test report. In this way, appropriate corrective measures can be taken in time and possible claims on system suppliers or manufacturers can be filed.

Monitoring of PV system quality

With our world-wide monitoring service, we measure important parameters for a system and its components, and determine the potential for optimisation. We compare the measured data with predictions and thus determine possible deviations from optimal system operation. The application of accurate measurement equipment and the use of irradiation sensors that have been calibrated according to international standards enable us to detect small deviations immediately. Our monitoring service is independent of operation monitoring as supplied by the inverter manufacturer. Clients receive a comprehensive, neutral evaluation of their systems and thus have an independent estimate of the performance of their technology under real operating conditions.

1 PV system (1 553 kWp) on the roof of the central ALDI warehouse in Adelsdorf.



MEASUREMENT OF BUILDING FAÇADES AND TRANSPARENT COMPONENTS

TestLab Solar Façades offers a comprehensive range of characterisation for innovative building components and materials to developers 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. 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

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

TestLab Solar Façades

Existing measurement procedures such as those specified in DIN EN 410 or DIN EN 13363 do not describe the properties of advanced glazing and façade constructions sufficiently reliably. Thus, we have developed testing and evaluation procedures to characterise energy and lighting-technology effects accurately.

Our equipment allows us to measure elements of more than 1 m^2 area, which have the following properties:

- light scattering and light redirection
- macroscopic structures and patterns
- angle-selective properties
- properties which change with time such as switchable transmittance (photochromic, thermotropic or electrochromic)
- air flow within the façade
- integrated photovoltaics

Different user profiles can also be taken into account in the evaluation procedures. Standard testing procedures round off our range of services. We use UV-vis-IR spectrometers to determine the spectral properties of glazing, films and surfaces for our clients.

Examples of equipment

- solar calorimeter to determine the total solar energy transmittance of transparent components and sun-shading devices
- thermal resistance measurements on glazing units according to DIN EN 674
- angle-dependent transmittance and reflectance measurements with large integrating spheres
- measurement of the angular distribution of transmitted and reflected light with a photogoniometer

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.

2 *Interior view of the rotatable daylight measurement room at Fraunhofer ISE.*

CALIBRATION OF PV AND CONCENTRATOR MODULES

Accurate determination of the performance data of solar cells and modules plays an important role in research and development, as well as production. It is vital for product comparison, and quality assessment of photovoltaic systems. Module manufacturers commission us to calibrate reference modules according to international standards for use in their production lines.

Boris Farnung, Tobias Gandy, Martin Jantsch, Jürgen Ketterer, Klaus Kiefer, Uli Kräling, **Frank Neuberger**, Gerhard Peharz, Peter Raimann, Michael Schachtner, **Gerald Siefer**

1 *Flasher laboratory 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.*

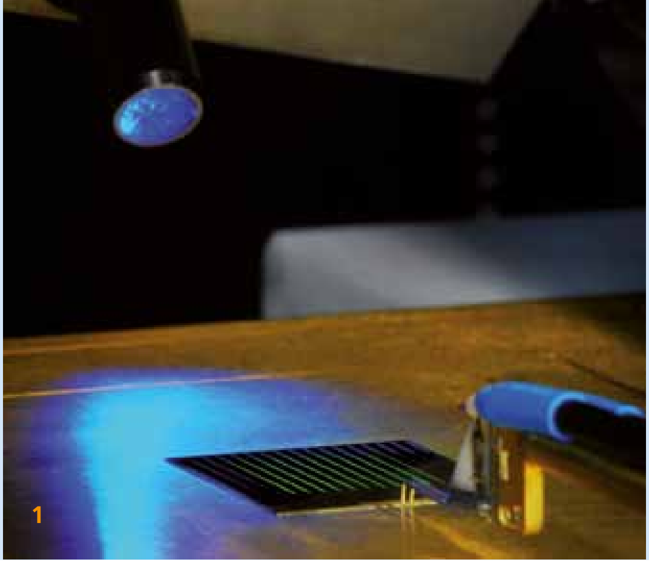
CalLab PV Modules (www.callab.de) at Fraunhofer ISE is one of the internationally leading photovoltaic calibration laboratories. The measurements are made with a Class A solar simulator according to IEC 60904-9. Traceability to international reference scales is achieved by use of primary-calibrated references, such as the reference solar cells and lamps calibrated by the Physikalisch-Technische Bundesansalt (PTB). All measurement equipment and procedures are included in a quality management system. We guarantee the reliability of our results by participating regularly in round-robin tests with other internationally recognised laboratories. The entire CalLab PV Modules is accredited according to ISO/IEC 17025.

Service spectrum

- measurement of the spectral response of individual cells of the modules or reference modules
- measurement of the current/voltage characteristics under standard test conditions (STC, 1000 W m^{-2}, AM 1.5g and 25 °C)
- measurement of the temperature and intensity dependence of module parameters
- determination of the open circuit voltage, short circuit current and fill factor, and rated power, current, voltage and efficiency value of modules

Measurement of concentrator modules

Standard measurements of concentrator modules are 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 took a laboratory test stand to measure concentrator module into operation in 2008. This is based on the provision of parallel light using a parabolic reflector with a diameter of 2 m.



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2

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. ISE 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, Astrid Ohm, Michael Schachtner, Holger Seifert, **Gerald Siefer**, **Wilhelm Warta**, Jutta Zielonka

1 *Spectral response measurement of a multi-junction solar cell with the grating monochromator set-up. In addition to the green light for measurement, blue bias light can be seen, which is used to bring the sub-cell being measured into the current-limited mode.*

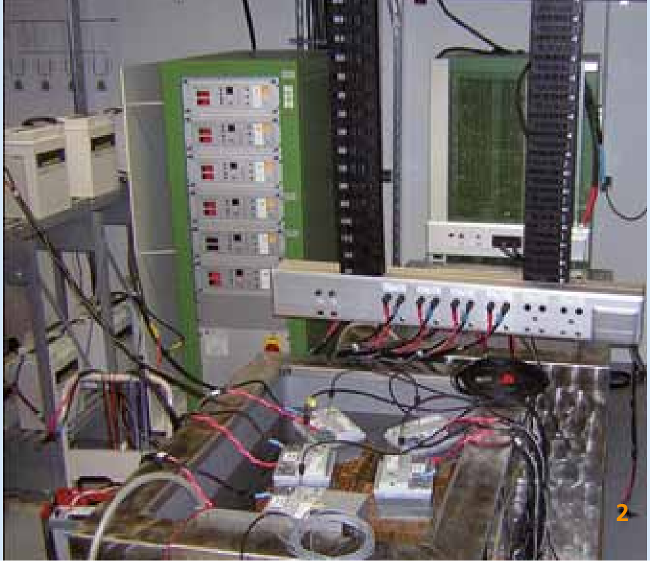
2 *Space solar cell during measurement of the calibrated current-voltage characteristic with the multi-source solar simulator.*

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 of Economics and Technology (BMWi) and the European Union (EU), and in co-operation with PV manufacturers, we work continuously on improving tolerances and developing new measurement procedures.

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.

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.



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 systems are 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 carry out electrical and thermal characterisation.

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

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 *Lead-acid batteries for the solar energy and automobile sectors are measured in a temperature-controlled water bath.*

Battery Technology

Specialised 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 battery systems with complex electronic controls are applied, which are based on lithium-ion or NiMH cells. Our battery laboratory is equipped with test units for all of these types of technology. Tests can be carried out according to the procedures specified by the relevant institutions (DIN, IEC, PVGAP and others), or according to customised algorithms.

Test conditions

We test batteries in a water bath or in a climatic chamber. 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.

EXTENSION OF THE TEST CAPACITY FOR HEAT PUMPS

We have applied our long years of experience in developing heat pumps for the low power range in extending our test capacity for heat pumps. Now we can offer our industrial clients the measurement of low-power equipment with different heat sources and sinks according to standards, and can comprehensively support equipment development experimentally and with system studies. Our work focuses on the system-optimised integration of heat sources and dimensioning of evaporators.

Nicolas Jaoutzis, Lukasz Kaczmarek, Hongwei Li, Duc Mac,
Marek Miara, Thore Oltersdorf, Jeannette Wapler

Since the 1990's, we have been working to improve the heat supply systems for zero-energy and passive buildings, and other similar categories of energy-efficient buildings.

One focus has been the further development of the smallest heat pumps, which mostly use exhaust air as the heat source. We have considerably extended our competence in the system evaluation of existing equipment in monitoring projects involving large numbers of low-power heat pump systems – previously for compact heating and ventilation units with exhaust-air heat pumps, currently for heat pump systems in new buildings and the existing building stock. 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.

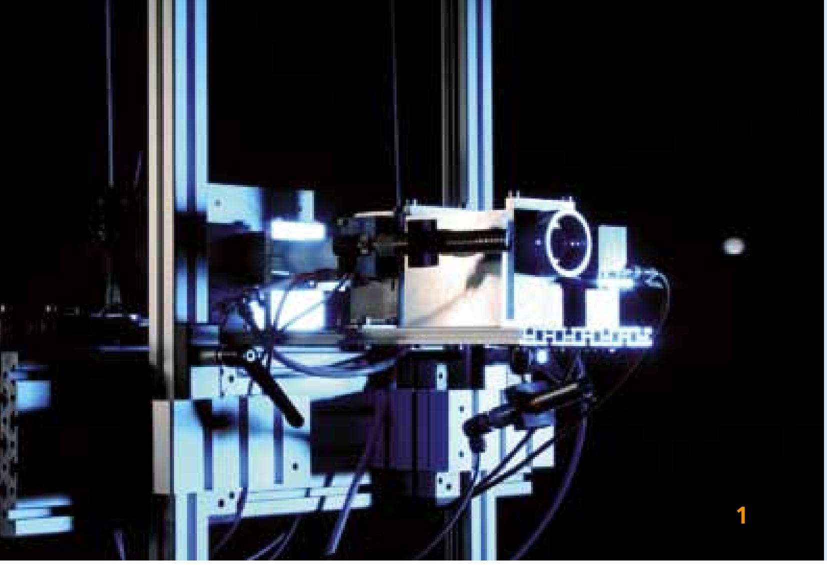
The working media of air, sols and water can be combined in our test stand to simulate different heat sources and sinks. The heating power range of the measured heat pumps can be up to 4 kW for air-water systems and up to 12 kW for systems working with sol-water or water-water combinations. Extension of the capacity for air-water systems also up to 12 kW heating power is planned.

In addition to evaluating the status quo of heat pumps in monitoring projects and in the test stand, we also offer support in the development of equipment. We focus on evaporators for the combination of different heat sources and the further development of soldered evaporators, which were conceived at Fraunhofer ISE and which we dimension and measure according to clients' specifications. Combinations with solar thermal energy systems are playing an increasing role in this development.

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

1 *Side view of sub-circuits to condition the hydraulic heat sinks or sources of our test stand. Most of the conditioning is implemented hydraulically, so that even the test stand can be operated with good energy efficiency.*

2 *Front view of the set of evaporators for the evaporator test stand. It is used for experimental investigation of the concepts that were developed at Fraunhofer ISE for air-exposed evaporators.*



TESTING OF SOLAR COLLECTORS AND COMPLETE SYSTEMS

TestLab Solar Thermal Systems is authorised by DIN CERTCO, CERTIF and SRCC, and is fully accredited by DAP (Deutsches Akkreditierungsrat Prüfwesen). We test solar collectors 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, Gerhard Stryi-Hipp, Christoph Thoma

1 *Hail impact test stand, which was designed and constructed at Fraunhofer ISE.*

2 *New double-axis precision tracker to measure innovative collector technology.*

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.

New testing possibilities and considerable expansion of the facility were implemented in 2009 for TestLab Solar Thermal Systems.

After installing a new tracker, Fraunhofer ISE is now equipped with two additional measurement rigs for characterising performance according to the stationary method. In addition, the tracker offers significantly greater degrees of freedom and applies yet more accurate control and measurement technology. Beyond this, our test spectrum was extended with two test rigs for the quasi-dynamic characterisation method. With these, all of the currently usual measurement methods are now available. In order to satisfy increased interest in short testing times, but also to allow testing in early spring and late autumn, two outdoor-exposure trackers were also taken into operation.

Hail impact test stand

In 2009, we took another new piece of equipment into operation, namely the second generation of the hail impact test stand designed at Fraunhofer ISE. It implemented more precise definition of the impact parameters, automatic sighting of the target and technical changes to improve safety.

Test stand for systems and storage tanks

Up to four complete hot water systems can be investigated in parallel according to DIN EN 12976-1,2:2006. In addition, the laboratory meets the specifications to carry out storage tank measurements according to EN 12977-3:2008.

Indoor collector test stand with a solar simulator

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. This laboratory is also completely accredited to conduct measurements according to DIN EN 12975-1,2:2006.

Medium-temperature testing unit up to 200 °C

Our medium-temperature testing unit has been operating since 2006. With it, we can measure efficiency curves for operating temperatures up to 200 °C. This means that it is feasible to carry out experimental development of process heat collectors in TestLab Solar Thermal Systems.

Test stand for solar air collectors

We also operate a test stand for solar air collectors, which can be used for outdoor measurements or integrated into the indoor test stand with the solar simulator. Solar air collectors are tested according to DIN EN 12975-1,2:2006 or ASHRAE 93.

3 *Extension of the test area with two new outdoor-exposure trackers and two test rigs for the dynamic measurement method.*

4 *Test facility to measure storage tanks according to EN 12977-3.*

VISITING SCIENTISTS

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Ioffe-Institute
St. Petersburg, Russia
23.7.2009–30.9.2009
Research area: Concentrator PV

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Bologna, Italy
16.10.2009–30.8.2010
Research area: Analyse of silicon surfaces with SPV

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1.3.2008–31.1.2009
Research area: Building technology

Priscilla Braun
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Florianópolis-SC, Brasil
1.4.2008–31.5.2009
Research area: Integration of PV systems and grid feedback

MSc.-ME Anthony R. Florita
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Research area: Building technology

Dr Hao Jin
The Australian National University
Canberra, Australia
7.–11.9.2009
Research area: Silicon solar cells

MSc.-Ing. Michele Liziero
Politecnico di Milano
Milan, Italy
16.8.2008–15.3.2009
Research area: Building technology

MSc.-Ing. Graziano Salvalai
Politecnico di Milano
Milan, Italy
16.7.2008–15.7.2009
Research area: Building technology

Dr Hele Irene Savin
University of Technology
Espoo, Finland
16.8.2009–28.2.2010
Research area: Light-induced Cu-defects in silicon solar cells

MSc.-Ing. Marta M. Sesana
Politecnico di Milano
Milan, Italy
1.11.2008–30.4.2009
Research area: Building technology

Dr Jean St. Pierre
University of South Carolina
Columbia, South Carolina, USA
13.4.–31.7.2009
Research area: Water management of fuel cells

MSc. (Tech.) Heli Talvitie
Helsinki University of Technology
Helsinki, Finland
1.12.2008–30.11.2009
Research area: Defect rearrangement by temperature-dependent treatments of silicon

Dr Klaus Weber
The Australian National University
Canberra, Australia
3.–10.6.2009
Research area: Silicon solar cells

MSc. (Sci) Jiang Zhu
Loughborough University
Centre for Renewable Energy System Technologies
Loughborough, Leicestershire, UK
1.–30.11.2009
Research area: Modelling of PV modules

PARTICIPATION IN ORGANISATIONS

Alliance for Rural Electrification, Member

Bavaria California Technology Center (BaCaTec), Board of Directors

Brennstoffzellen-Allianz Baden-Württemberg (BzA-BW), Member and Executive Committee

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

Bundesverband Solarwirtschaft (BSW), Arbeitskreis Ländliche Elektrifizierung, Member

CAN in Automation (CiA), 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 Gesellschaft für Nachhaltiges Bauen e. V. (DGNB), Member

Deutsche Gesellschaft für Sonnenenergie e. V. (DGS), Member

Deutsche Meerwasserentsalzung e. V. (DME), 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*

EU PV Technology Platform
- *Steering Committee, Vice-Chairman*
- *Working Group »Developing Countries (WG4)«, Member*
- *Working Group »Science, Technology & Applications (WG3)«, Member*

Europäisches Komitee für Normung
- *CEN TC33/WG3/TG5, Member*
- *CEN TC312/WG1 und 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

Evergreen Solar, Marlboro, USA, Scientific Advisory Council

Expertenkommission der Bundesregierung »Forschung und Innovation«, Member

Fachausschuss Tageslicht der Lichttechnischen Gesellschaft (LitG), Member

Fachinstitut Gebäude-Klima (FGK), Arbeitskreis »Expertenkreis Klimaschutz«, Member

Fachverband Transparente Wärmedämmung e. V., Member

FIT Mikroenergietechnik, Member and Executive Committee

PARTICIPATION IN ORGANISATIONS

FitLicht – Fördergemeinschaft innovative Tageslichtnutzung, Member

Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW e. V.), Arbeitskreis Photovoltaik, Member

ForschungsVerbund Erneuerbare Energien (FVEE), Member and Spokesperson

Fraunhofer-Allianz Bau, Member

Fraunhofer-Allianz Energie, Manager and Spokesperson

Fraunhofer-Allianz Nanotechnologie, Member

Fraunhofer-Allianz Optic Surfaces, Member

Fraunhofer-Allianz SysWasser, Member

Fraunhofer-Netzwerk Batterien, Member

Fraunhofer-Netzwerk Intelligente Energienetze, Co-ordination

Fraunhofer-Netzwerk Windenergie, Member

Fraunhofer Systemforschung Elektromobilität, Member

Fraunhofer-Themenverbund Oberflächentechnik und Photonik, Guest 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

Global Village Energy Partnership (GVEP), Member

International Advisory Committee of EUPVSEC, Member

International Advisory Committee of SIMC, Member

International Electrotechnical Commission IEC/TC82/WG7, Concentrator Modules, Member

International Energy Agency IEA, Member:
Solar Heating & Cooling Programme SHCP
- *Task 43 »Solar Rating and Certification Procedure – Advanced Solar Thermal Testing and Characterization for Certification of Collectors and Systems«*
- *Task 33/4 »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«*

International Organization for Standardization ISO/TC180/SC4, Member

International Program Committee of GADEST, Member

International Science Panel on Renewable Energies (ISPRE), President

Intersolar North America, Program Commitee, Chair

Kompetenzfeld Photovoltaik NRW, Member

Kompetenznetzwerk Brennstoffzelle NRW, Member

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), (Task Force), Member

Stiftung Solarenergie, Advisory Board

Symposium Photovoltaische Solarenergie, Scientific Advisory Board

VDI-Gesellschaft Technische Gebäudeausrüstung
- *Richtlinienausschuss 6018*
- *Richtlinienausschuss 4650, Blatt 1 und Blatt 2*

VDMA – The German Engineering Federation
- *Productronics Association, Member*
- *Deutsches Flachdisplay-Forum (DFF), Member*
- *Organic Electronics Association (OE-A), Member*

VDMA Brennstoffzellen
Arbeitskreis Industrienetze, Member

Verband zu Energieeffizienz in Gebäuden, Founding member

Verein Deutscher Ingenieure (VDI)
VDI-Gesellschaft Energietechnik
- *Fachausschuss »Regenerative Energien« (VDI-FA-RE)*

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

Weiterbildungszentrum WBZU »Brennstoffzelle«, Member Board of Directors

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

TRADE FAIRS

24. Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, 4.–6.3.2009

Hannover Messe Industrie
Hannover, 20.–24.4.2009

Intersolar
Internationale Fachmesse und
Kongress für Solartechnik
München, 27.–29.5.2009

Hydrogen & Fuel Cells 2009
Conference and Trade Show
Vancouver, 31.5.–3.6.2009

Intersolar North America
San Francisco, USA, 14.–16.7.2009

Clean-Tech Award 2009
Berlin, 10.9.2009

24th European Photovoltaic Solar Energy
Conference and Exhibition
Hamburg, 21.–25.9.2009

f-cell
Stuttgart, 28./29.9.2009

CONGRESSES, CONFERENCES AND SEMINARS

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

14. Symposium Licht + Architektur (OTTI)
Kloster Banz, Bad Staffelstein, 12.–13.2.2009
(Member of the Scientific Committee)

6. Workshop SiliconFOREST
Fortschritte in der Entwicklung von Solarzellen-Strukturen und Technologien
Falkau, 1.–4.3.2009

24. Symposium Photovoltaische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, 4.–6.3.2009

2. Anwenderforum Energetische Sanierung von Gebäuden (OTTI)
Kloster Banz, Bad Staffelstein, 26./27.3.2009
(Member of the Scientific Committee)

19. Symposium Thermische Solarenergie (OTTI)
Kloster Banz, Bad Staffelstein, 6.–8.5.2009
(Member of the Scientific Committee)

Power Electronics for Photovoltaics (OTTI)
München-Dornach, 25./26.5.2009

5th PV Industry Forum, Intersolar
München, 25./26.5.2009
(Advisory Board)

Small PV Applications (OTTI)
Ulm, 25./26.5.2009
(Member of the Scientific Committee)

34th IEEE Photovoltaic Specialists Conference (PVSC),
Philadelphia, PA, USA, 7.–12.6.2009

24th European Photovoltaic Solar Energy Conference and Exhibition
Hamburg, 21.–25.9.2009

3rd Conference Solar Air-Conditioning (OTTI)
Palermo, 30.9.–2.10.2009
(Member of the Scientific Committee)

International BuildingEQ Symposium
Linking EPBD and Commissioning
Berlin, 30.9.–1.10.2009

Fachforum Netzferne Stromversorgung mit Photovoltaik (OTTI)
Freiburg, 6.–8.10.2009

Solar Summits Freiburg
International Conference on Renewable and Efficient Energy Use
Solar Buildings
Freiburg, 12.–16.10.2009

Workshop MWT Solar Cells and Modules
Freiburg, 14./15.10.2009

FVEE-Jahrestagung
Forschen für globale Märkte erneuerbarer Energien
Berlin, 24./25.11.2009

4. Internationale Konferenz zur Speicherung Erneuerbarer Energien IRES
Berlin, 24./25.11.2009
(Member of the Scientific Committee)

Power MEMS
The 9th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications
Washington D.C., USA, 1.–4.12.2009

DOCTORAL THESES

Rainer Becker: „Entwurf und Betrieb von Regelungs- und Monitoringsystemen für dezentrale Energiesysteme auf der Basis von verteilten Embedded Systems" (Design and operation of control and monitoring systems for decentralised energy systems based on distributed embedded systems), Universität Kassel, Kassel, 2009

Florian Clement: „Die Metal Wrap Through Solarzelle" (The Metal Wrap Through Solar Cell), Albert-Ludwigs-Universität Freiburg, Freiburg, 2009

Stephan Diez: „Lebensdauerspektroskopie metallischer Defekte in Silicium und Analyse monokristalliner Materialalternativen" (Lifetime spectroscopy of metal defects in silicon and the analysis of monocrystalline material alternatives), Universität Konstanz, Konstanz, 2009

Francesco Frontini: "Daylight and Solar Control in Buildings General Evaluation and Optimization of a New Angle Selective Glazing Façade", Politecnico di Milano, Milano, 2009

Dietmar Gerteisen: „Untersuchung des Massentransports in der Brennstoffzelle auf unterschiedlichen Skalenebenen mit Hilfe mathematischer Modellierung" (Investigation of the mass transport in the fuel cell on different levels of scale using mathematical modelling), Universität Konstanz, Konstanz, 2009

Jan Christoph Goldschmidt: "Novel Solar Cell Concepts", Universität Konstanz, Konstanz, 2009

Filip Granek: "High-Efficiency Back-Contact Back-Junction Silicon Solar Cells", Albert-Ludwigs-Universität Freiburg, Freiburg, 2009

Christina Hildebrandt: „Hochtemperaturstabile Absorberschichten für linear konzentrierende solarthermische Kraftwerke" (High-temperature stable absorber coatings for linear concentrating solar thermal power stations), Universität Stuttgart, Stuttgart, 2009

Matthias Hörteis: "Fine Line Printed Contacts on Crystalline Silicon Solar Cells", Universität Konstanz, Konstanz, 2009

Doreen Kalz: "Heating and Cooling Concepts Employing Environmental Energy and Thermo-Active Building Systems for Low-Energy Buildings: System Analysis and Optimization", Universität Karlsruhe, Karlsruhe, 2009

Stefan Kontermann: "Characterization and Modelling of Contacting Crystalline Silicon Solar Cells", Universität Konstanz, Konstanz, 2009

Kuno Mayer: „Chemische Ansätze zur Neuordnung des Solarzellenprozesses ausgehend vom Wafering bis hin zur Emitterdiffusion" (Chemical approaches for reordering the solar cell process from wafering through to emitter diffusion), Johann Wolfgang Goethe-Universität Frankfurt am Main, Frankfurt, 2009

Nicola Mingirulli: "Fabrication and Characterization of Emitter Wrap Through Solar Cells", Universität Konstanz, Konstanz 2009

Marius Peters: "Photonic Concepts for Solar Cells", Albert-Ludwigs-Universität Freiburg, Freiburg, 2009

Lena Schnabel: „Experimentelle und numerische Untersuchung der Adsorptionskinetik von Wasser an Adsorbens-Metallverbundstrukturen" (Experimental and numerical investigation of the kinetics of adsorption of water on adsorbent-metal composite structures), Technische Universität Berlin, Berlin, 2009

Jan Schöne: „Kontrolle von Spannungsrelaxation und Defektbildung in metamorphen III-V-Halbleiterheterostrukturen für hocheffiziente Solarzellen" (Controlling voltage relaxation and defect formation in metamorphic III-V semiconductor heterostructures for high efficiency solar cells), Christian-Albrechts-Universität Kiel, Kiel, 2009

Olivier Stalter: "Inverter-Integrated, Sensorless and Power-Optimized Position Control of a Concentrating Photovoltaic Dual-Axis Tracker", Grenoble Electrical Engineering G2ELab (INPG), Grenoble, 2009

Catherine Voyer: „Innovative Technologien zur Emittererzeugung für kristalline Silizium-Solarzellen mittels Durchlaufdiffusion", (Innovative technologies for emitter formation of crystalline silicon solar cells using in-line diffusion), Albert-Ludwigs-Universität Freiburg, Freiburg, 2009

Jan Wienold: "Daylight Glare in Offices", Universität Karlsruhe, Karlsruhe, 2009

LECTURE COURSES AND SEMINARS

Dr Thomas Aicher, Dr Tom Smolinka
"Energieverfahrenstechnik"
Vorlesungen WS 08/09 und WS 09/10
Hochschule Offenburg
Studiengang Elektrotechnik/Informationstechnik^{Plus}

Dr Dietmar Borchert
"Photovoltaik"
Vorlesung SS 09
TFH Georg Agricola zu Bochum
Fachbereich Maschinentechnik

Prof Bruno Burger
"Solar-Technologien"
Vorlesung SS 09
Berufsakademie Ravensburg
Studiengang Elektrotechnik-Automatisierungstechnik

Prof Bruno Burger
"Leistungselektronische Systeme für regenerative Energiequellen"
Vorlesung WS 09/10
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

Dr Stefan Glunz
"Photovoltaische Energiekonversion"
Vorlesung SS 09
Albert-Ludwigs-Universität Freiburg
Technische Fakultät

Dr Stefan Glunz, Dr Ralf Preu
"Elective 1 – Photovoltaics Part 1: Theory"
Vorlesung SS 09
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Dr Stefan Glunz, Dr Werner Platzer, Dr Ralf Preu,
Dr Christof Wittwer
"Technology I"
Vorlesung WS 09/10
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Dr Stefan Henninger, Dr Peter Schossig
Module "Research Skills" WS 09/10
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Sebastian Herkel
"Solare Energiesysteme"
Vorlesung WS 08/09
Staatliche Akademie der Bildenden Künste, Stuttgart
Studiengang Architektur

Florian Kagerer
"Solare Energiesysteme"
Vorlesung WS 09/10
Staatliche Akademie der Bildenden Künste, Stuttgart
Studiengang Architektur

Doreen Kalz
"Klimagerechtes Bauen und Einsatz von Phasenwechselmaterialien"
Vorlesung SS 09
Hochschule Offenburg
Studiengang Versorgungstechnik

Anton Neuhäuser
"Concentrating Solar Power"
Vorlesung WS 09/10
Technische Universität Berlin
Studiengang Global Production Engineering

Dr Jens Pfafferott
"Solares Bauen"
Präsenzveranstaltung SS 09 und WS 09/10
Universität Koblenz-Landau
Fernstudiengang Energiemanagement

Norbert Pfanner
"Solartechnologie"
Vorlesung SS 09
Hochschule Offenburg
Studiengang Elektrotechnik/Informationstechnik^{Plus}

Dr Werner Platzer
"Elective I – Solar Radiation and Solar Systems"
Vorlesungsmodul SS 09
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Dr Werner Platzer
"Thermische Solarenergie"
Präsenzveranstaltung WS 09/10
Universität Koblenz-Landau
Fernstudiengang Energiemanagement

Dr Ralf Preu
"Elective 1 – Photovoltaics Part 2: Production Technology"
Vorlesung SS 09
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Dr Ralf Preu, Dr Christof Wittwer, Dr Werner Platzer
"Technology I"
Vorlesung WS 08/09
Albert-Ludwigs-Universität Freiburg
Zentrum für Erneuerbare Energien (ZEE)
Studiengang Renewable Energy Management (REM)

Prof Dr Roland Schindler
"Photovoltaik I"
Vorlesung WS 08/09
"Photovoltaik II"
Vorlesung SS 09
Fernuniversität Hagen
Fakultät für Mathematik und Informatik
Fachrichtung Elektrotechnik und Informationstechnik

Dr Heribert Schmidt
"Photovoltaische Systemtechnik"
Vorlesung SS 09
Universität Karlsruhe
Fakultät für Elektrotechnik und Informationstechnik

Prof Dr Eicke R. Weber
"Neue Konzepte in der Photovoltaik"
Oberseminar SS 09
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof Dr Eicke R. Weber, Dr Uli Würfel
"Photovoltaische Energiekonversion"
Vorlesung SS 09
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof Dr Eicke R. Weber
"Photovoltaik"
Oberseminar WS 09/10
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof Dr Eicke R. Weber, Dr Werner Platzer
"Solarthermie"
Vorlesung WS 09/10
Albert-Ludwigs-Universität Freiburg
Fakultät für Physik und Mathematik

Prof Dr Gerhard Willeke, Dr Giso Hahn
"Halbleitertechnologie und Physik der Solarzelle"
Vorlesung WS 08/09
Universität Konstanz
Fachbereich Physik

PATENTS

PATENTS GRANTED

Andreas Schmitz, Christopher Hebling, Bruno Burger, Robert Hahn[1]
"Fuel cell systems in printed circuit board technology"
([1]: Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration IZM, Berlin)

Heribert Schmidt, Christoph Siedle, Jürgen Ketterer
"Inverter for converting electrical direct current into alternating current or voltage"

Andreas Hinsch, Udo Belledin, Ronald Sastrawan, Andreas Georg
"Photoelectrochemical solar cell module"

Kuno Mayer, Daniel Kray, Sybille Hopman, Bernd Kolbesen[1]
"Procedure for microstructuring solid state surfaces"
([1]: Johann Wolfgang Goethe-Universität, Frankfurt am Main)

Stefan Reber, Albert Hurrle, Norbert Schillinger
"Apparatus and procedure for continuous gas phase epitaxy under atmospheric pressure and its application"

Philipp Ettle, Markus Bergmann, Daniel Kray, Fridolin Haas
"Wire saw with controllable wire field"

Andreas Bett, Joachim Jaus
"Photovoltaic module and its uses"

Jan Christoph Goldschmidt, Philipp Löper, Marius Peters
"Solar element with increased efficiency and procedure for increasing efficiency"

Heribert Schmidt, Bruno Burger
"Inverter"

Michael Oszcipok
"Passive dilution unit for dilution of fuels"

Bruno Burger, Heribert Schmidt
"Controllable switching apparatus for a solar module"

PATENT APPLICATIONS

Oliver Schultz-Wittmann, Filip Granek, Martin Hermle, Jan Benick
"Superimposed doping to optimise single-sided contact solar cells"

Florian Clement, Daniel Biro, Michael Menkö, Tim Kubera
"Edge-connected solar cells as well as procedures for their manufacture"

Bruno Burger, Heribert Schmidt
"Isolating circuit for inverters"

Adolf Goetzberger, Michael Procida
"New support system for the erection of photovoltaic systems in open spaces and its use (SEIL-System)"

Robert Szolak, Alexander Susdorf, Thomas Aicher
"Equipment and vaporisation from liquid fuels and flammable liquids"

Ralf Preu, Andreas Grohe, Daniel Biro, Jochen Rentsch, Marc Hofmann, Andreas Wolf, Jan Nekarda
"Structure and procedure for local high doping and structuring of a solar cell"

Birger Zimmermann, Michael Niggemann, Hans-Frieder Schleiermacher
"Method for the structurised coating of substrates"

Michael Niggemann, Birger Zimmermann
"Stacked solar cell with reflecting interlayer as well as assembly of this solar cell"

Harry Wirth
"Photovoltaic module and procedure for its manufacture"

Markus Büttner
"Procedure for itemising the electrical consumption of a number of electrical devices and the equipment for this process"

Kuno Mayer, Daniel Kray
"Procedure and equipment for simultaneous microstructuring and passivation"

Kolja Bromberger, Christian König, Volker Ackermann
"Low-temperature fuel cell with integrated water management system for the passive output of product water"

Matthias Hörteis, Aleksander Filipovic, Christian Seitz
"Aerosol printer, use and procedure for manufacturing line interruptions by continuous aerosol print processes"

Jan Christoph Goldschmidt, Marius Peters, Martin Hermle, Philipp Löper, Benedikt Bläsi
"Luminescence collector with at least one photonic structure with at least one luminescent material as well as the contained solar cell module"

Filip Granek, Daniel Kray, Kuno Mayer, Monica Alemán, Sybille Hopmann
"Solar cells with back-side contacts as well as their manufacturing procedure"

Filip Granek, Daniel Kray, Kuno Mayer, Monica Alemán, Sybille Hopmann
"Front and back-surface contacted solar cells as well as their manufacturing procedure"

Karl-Heinz Priewasser[1], Daniel Kray, Marius Peters
"Jet unit, Procedure for manufacturing a jet unit as well as an apparatus with a jet unit"
([1]: DISCO-HI-TEC EUROPE GmbH)

Hans-Martin Henning, Constanze Bongs, Michael Hermann
"Apparatus for distributing fluids and their heat and/or material transfer"

Gerhard Peharz, Peter Nitz, Thomas Schmidt, Armin Bösch, Joachim Jaus, Andreas Bett
"Solar cell construction group as well as solar cell assembly"

Kuno Mayer, Ingo Krossing[1], Carsten Kanpp[1], Filip Granek, Matthias Mesec, Andreas Rodofili
"Apparatus and procedure for the simultaneous microstructuring and doping of semiconductor substrates"
([1]: Albert-Ludwigs-Universität, Freiburg)

Joachim Went
"Printer exchanger with linear drive"

Wolfram Kwapil, Markus Glatthaar, Stefan Rein, Daniel Biro
"Restricting hot spot development of a solar cell in a module by restricting local field peaks"

Wolfgang Guter, Frank Dimroth, Jan Schöne
"Tunnel diodes from voltage-compensated compound semiconductor layers"

Harry Wirth, Hans-Ulrich Wagner[1], Jens Kalmbach[2], Bernd Hirzler[3]
"Photovoltaic module with planar cell connector"
([1]: aleo solar AG), ([2]: Schmidt Technology Systems GmbH), ([3]: Somont GmbH)

Hans-Martin Henning, Andreas Holm[1]
"Procedure for self-cleaning the surface of solar energy systems (photovoltaic modules, solar thermal systems)"
([1]: Fraunhofer Institute for Building Physics IBP, Stuttgart)

Marius Peters, Benedikt Bläsi, Jan Christoph Goldschmidt
"Photovoltaic concentrator system, solar cell and concentrator system with an angle-selective filter as secondary concentrator"

Marius Peters, Gerhard Peharz, Jan Christoph Goldschmidt, Philipp Löper
"Procedure to realise up and down conversion for photovoltaic concentrator applications"

Benedikt Bläsi, Marius Peters, Jan Christoph Goldschmidt, Martin Hermle, Hubert Hauser, Pauline Voisin
"Structuring concept for an efficient light trapping in silicon solar cells"

Martin Hermle, Hubert Hauser, Pauline Voisin, Benedikt Bläsi, Marius Peters, Jan Christoph Goldschmidt
"Silicon solar cell with nanostructured a-Si back side"

Isolde Reis
"Procedure for improving the quality of wafers as well as applying the procedure"

Harry Wirth
"Apparatus for concentrating and converting solar energy"

Heribert Schmidt, Werner Roth
"Bypass switching and protective switching for solar module"

Evelyn Schmich, Matthias Hörteis, Stefan Glunz
"Production of a contact layer rich in defects"

Thore Oltersdorf, Nils Paust
"Fluid distributing element with raw materials flow having one or more phases using centrifugal force"

REVIEWED JOURNALS

Aicher, T.; Full, J.; Schaadt, A.
»A Portable Fuel Processor for Hydrogen Production from Ethanol in a 250 W_{el} Fuel Cell System«, in: Journal of Power Sources, Vol. 34, No. 19, pp. 8006–8015

Bartsch, J.; Radtke, V.; Schetter, C.; Glunz, S. W.
»Electrochemical Methods to Analyse the Light-Induced Plating Process«, in: Journal of Applied Electrochemistry, published online

Benick, J.; Richter, A.; Hermle, M.; Glunz, S. W.
»Thermal Stability of the Al_2O_3 Passivation on p-Type Silicon Surfaces for Solar Cell Applications«, in: physica status solidi – Rapid Research Letters, Vol. 7–8, pp. 233–235

Bergmann, A.; Gerteisen, D.; Kurz, T.
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CONFERENCES AND TRADE FAIRS IN 2010 WITH FRAUNHOFER ISE PARTICIPATION:

25. Symposium Photovoltaische Solarenergie, Kloster Banz, Bad Staffelstein 3.–5.3.2010

6. International Conference on Concentrating Photovoltaic Systems, Freiburg, 7.–9.4.2010

Hannover Messe, Hannover, 19.–23.4.2010

20. Symposium Thermische Solarenergie, Kloster Banz, Bad Staffelstein, 5.–7.5.2010

Intersolar, München, 9.–11.6.2010

Intersolar North America, San Francisco, 13.–15.7.2010

16th International SolarPACES Conference, Perpignan, 21.–24.9.2010

f-cell Forum, Stuttgart, 27.–28.9.2010

25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia, 6.–10.9.2010

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