Fraunhofer

ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2014/15

Cover photo:
Single-surface in-line copper deposition on silicon solar cells with light-induced electroplating: Electrochemical processes to create solar cell contacts have already been investigated at Fraunhofer ISE for several years. They are rapid, inexpensive and run at low temperatures. Relatively well established processes, such as the completely galvanic construction of solar cell contacts of nickel, copper and tin, are already very close to market introduction. In the illustrated, industrially relevant copper deposition facility, samples for the first customers are being prepared by Fraunhofer ISE in cooperation with its industrial partners. Parallel to this, Fraunhofer ISE is researching very innovative procedures such as the electrochemical structuring of aluminium (page 32). Expertise on electrochemical aspects, combined with process technology, led to the idea of a completely new structuring approach, which enables metal structuring for diverse, advanced cell concepts at low temperatures in a single, simple processing step. (Photo: Achim Käflein)

FOREWORD

Last year, Fraunhofer ISE was able to harvest the fruits of its R&D work in the form of several major awards and honours. At the beginning of 2014, Sheikh Mohammed Bin Zayed Al Nahyan, the Crown Prince of Abu Dhabi, presented me with the Zayed Future Energy Prize for Fraunhofer ISE at the World Future Energy Summit in Abu Dhabi. This prize, accompanied by prize money of 1.5 million US dollars, was awarded to the Institute in the Non-Governmental Organization category for its influence on the currently evident industrial, social and ecological transformation, its leadership role and example and finally its sustainability and innovation potential. We have invested the prize money in a funding programme, which the Board of the Fraunhofer-Gesellschaft has doubled. The money is now being used as seed financing for sustainable energy projects in countries outside Germany (page 13).

A great honour was also bestowed upon Dr Stefan Glunz, Director, Division "Solar Cells – Development and Characterization" at Fraunhofer ISE and one of the internationally leading scientists in the field of high-efficiency photovoltaics of the next and subsequent generations. The EU Commission awarded him the Becquerel Prize in September, thereby recognizing the excellent pioneering work on highly efficient silicon solar cells of our long-standing colleague. In particular, the broad bandwidth of his approaches to increase efficiency and thus reduce costs for photovoltaic power generation was emphasized. The approaches range from investigating electrically active defects in the cells themselves, through savings in material consumption, to numerous innovations in production technology.

The list of further awards and prizes (page 12) conferred for R&D work at Fraunhofer ISE in 2014 also includes the Laser Technology Award. In May, Dr Ralf Preu, Director, Division "Photovoltaic Production Technology and Quality Assurance", Dr Jan Nekarda and Martin Graf received the "Innovation Award Laser Technology 2014" for their work on laser-fired contacts (LfC) for highly efficient solar cells. This European science prize is awarded every second year by the Arbeitskreis Lasertechnik e.V. and the European Laser Institute ELI. The excellent work of scientists at our Institute was also documented by the three new professorships which were granted in 2014. In January, the Institute Deputy Director and Director, Division "Energy-Efficient Buildings", Prof. Hans-Martin Henning accepted the Chair for Technical Energy Systems at the Faculty for Mechanical Engineering at the Karlsruhe Institute of Technology. Prof. Christof Wittwer became an honorary professor of the Faculty for Environment and Natural Resources at the University of Freiburg and Dr Stefan Glunz was offered to become the Professor for Photovoltaic Energy Conversion in the Technical Faculty of the University of Freiburg.

We also celebrated two new world records for concentrator photovoltaics in 2014. The FLATCON® module technology developed at Fraunhofer ISE attained an efficiency value of 36.7 %. This was achieved by adapting the lenses to a new solar cell structure. In addition, we cooperated with Soitec and CEA-Leti to further develop the required multi-junction solar cells, which set a new world efficiency record of 46 % for the conversion of sunlight into electricity.

Despite all scientific excellence, 2014 was an economically difficult year for Fraunhofer ISE, as it was for the entire solar sector in Germany. Due to the large production overcapacity which had been built up over the previous years throughout the world, the number of orders for new PV production facilities declined dramatically and many equipment manufacturers now struggle to survive. The prices for PV modules fell to below 50 $ct/Watt. At the same time, these depressed prices led to such low costs for PV electricity – much less than 10 $ct/kWh in sunny regions – that the market for photovoltaics is continuing to boom. For the year 2014 new installations amounting to more than 46 GW are expected. However, it is probable that Germany will slip back to fifth place for new installations, behind China, USA, Japan and Great Britain.

In Germany, the most recent decisions concerning the Renewable Energy Act EEG have not provided any tailwind for the PV industry or the energy transformation. PV electricity generated and used on-site by plants with an installed capacity exceeding 10 kW is being penalized with a fee, which has not improved the climate for investors. In Germany, the capacity of newly installed PV plants in 2014 was probably less than 2000 MW, even less than the projected "extension corridor", which itself is considered to be very low. The branch analysts now generally assume that the reduced global production capacity resulting from insolvencies and mergers will soon stabilize near the anticipated global market volume for 2016–17. Plans for capacity expansion are already stimulating the first noticeable signs of an upswing also for manufacturers of PV production equipment. As a result, we now view the state of the solar industry with some optimism.

To equip Fraunhofer ISE to optimally meet the demands of the "Energiewende" and the industry, we had structured the Institute in 2013 into twelve new business areas and eleven fields of competence. This Annual Report also follows this structure. During the past year, we discussed the strategies followed by these business areas in detail with auditors from the industry, so that the Institute can become yet more efficient and effective in future. Overall, we can describe the current situation of Fraunhofer ISE as a consolidation phase, which is also beneficial to many of the Institute structures after the years of turbulent growth from 2006 to 2013. We are now well prepared for further developments within the solar sector.

Fraunhofer ISE continues to promote the xGW_p project. We are cooperating with the CEA / INES and CSEM institutes within a German-French-Swiss consortium to establish a globally competitive production plant for the most recent PV technology, to be located in Europe. The goal is to help making the European PV industry competitive again, applying new cell and production technologies, ready for the time when the world-wide demand will revive dynamically. Another activity following the same strategy is the "Vallis Solaris" project, which aims to build up a simple, vertical PV production chain and thus establish local photovoltaic activity in sunny European countries without the need for a feed-in tariff.

We have also reinforced our international activities in another respect. During the third German-Chilean Mining and Raw Material Forum in Berlin, I signed an agreement concerning the establishment of a second Fraunhofer Center in Chile in the presence of the Chilean President, Michelle Bachelet, and the Fraunhofer President, Prof. Reimund Neugebauer. The "Center for Solar Energy Technologies (CSET)" will address photovoltaics, solar heat and water purification. CSET is affiliated with "Fraunhofer Chile Research".

Together with Fumio Murata, the Governor of Fukushima Prefecture, we have signed a Memorandum of Understanding, which is intended to support Fukushima in establishing a research centre for renewable energy. Research, testing and training activities are the subject of a cooperation agreement with the King Abdulla City for Atomic and Renewable Energy, K.A. CARE in Riyadh, Saudi Arabia.

Fraunhofer ISE participates in many international networks, not only with cooperation agreements and memoranda of understanding but also via the guest scientists who are active at our Institute (pages 150/151). We plan to expand these activities further in the coming years. My election to the office of President of the Association of European Renewable Energy Research Centres EUREC will also contribute to this process.

Starting in January 2015, I intend to work in this position to better integrate the national interest groups within Europe and thus make EUREC a strong discussion partner for the EU Commission and the EU Parliament.

Fraunhofer ISE has assumed responsibility for correctly presenting the often distorted facts that are used in energy-political discussions. For several years already, we have gathered the energy data for Germany from different sources and subjected them to scientific analysis. Since 2014, we have also made the complete set of data freely and quickly available via the Internet. Data on electricity generation from all conventional and renewable sources, import and export can now be accessed and presented in individually tailored graphs under www.energy-charts.de. The extremely large number of visitors to this site confirms that our tool is making a valuable contribution to data transparency (page 131).

Together with the other four Fraunhofer Institutes in Freiburg and the University of Freiburg, we initiated a new series of events in October 2014. The "Sustainability Summit" is the successor to the "Solar Summit" which had been held annually in Freiburg since 2008. The spectrum of topics treated has been broadened appreciably for the new event format. It underlines Freiburg's international pioneering role with regard to sustainability research. The event addresses the current transformation to a sustainable lifestyle, not only by providing technological solutions, but also by considering social acceptance and appropriate legal and economic boundary conditions. In coming years, this conference is intended to publicize the excellent research conducted in Freiburg in the broad area of sustainable development.

We are pleased to announce another event that is evidence for the good cooperation between the University and the Fraunhofer Institutes in Freiburg, namely the foundation of a third institute within the Technical Faculty of the University in 2015, the "Institute for Sustainable Systems Engineering ISSE".

Finally, 2014 also brought me a special personal honour. On my 65th birthday in October, I was awarded the Fraunhofer Medal, for which I am sincerely grateful. I have been asked to continue for some time as the Institute Director of Fraunhofer ISE, striving in this function towards a zero-CO_2 global energy supply.

Speaking for the whole Institute I would like to express our heartfelt gratitude to our Board of Trustees, auditors, scholarship donors, our contact persons in the Ministries on the Federal and State levels and funding bodies – particularly our industrial partners – for the continued funding and support of Fraunhofer ISE during the past year.

Current lectures and publications from Prof. Eicke R. Weber:
www.ise.fraunhofer.de/en/publications/lectures-and-talks-prof-weber

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1 The Institute Directorate of Fraunhofer ISE (from left to right): Prof. Hans-Martin Henning, Deputy Director and Business Area Coordinator for "Energy Efficient Buildings", Dr Andreas Bett, Deputy Director and Business Area Coordinator for "III-V and Concentrator Photovoltaics", Prof. Eicke R. Weber, Institute Director, Dr Holger Schroeter, Chief Financial Officer.

2 Dr Uli Würfel, Business Area Coordinator for "Dye, Organic and Novel Solar Cells", Dr Ralf Preu, Business Area Coordinator for "Silicon Photovoltaics", Dr Harry Wirth, Business Area Coordinator for "Photovoltaic Modules and Power Plants", Dr Stefan Glunz, Business Area Coordinator for "Silicon Photovoltaics" (from left to right).

ORGANIZATIONAL STRUCTURE

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Deputy Directors	Dr Andreas Bett Prof. Hans-Martin Henning	+49 761 4588-5257 +49 761 4588-5134
Chief Financial Officer	Dr Holger Schroeter	+ 49 761 4588-5668
Press and Public Relations	Karin Schneider	+49 761 4588-5150
Strategic Planing	Dr Thomas Schlegl	+49 761 4588-5473
Energy Policy	Gerhard Stryi-Hipp	+49 761 4588-5686
Coordinator for Photovoltaics	Prof. Gerhard Willeke	+49 761 4588-5266

Fraunhofer ISE is supported by long-standing mentors and experts in the solar energy branch: Prof. Adolf Goetzberger (Founder of the Institute and Institute Director 1981–1993), Prof. Joachim Luther (Institute Director 1993–2006) and Prof. Volker Wittwer (Deputy Institute Director 1997–2009).

3 *Dr Thomas Schlegl, Business Area Coordinator for "Energy System Analysis", Dr Günther Ebert, Business Area Coordinator for "Energy Efficient Power Electronics", Prof. Christof Wittwer, Business Area Coordinator for "System Integration and Grids – Electricity, Heat, Gas", Ulf Groos, Business Area Coordinator for "Zero-Emission Mobility" (from left to right).*

4 *Dr Peter Schossig, Business Area Coordinator for "Storage Technologies", Dr Werner Platzer, Business Area Coordinator for "Solar Thermal Technology", Dr Christopher Hebling, Business Area Coordinator for "Hydrogen and Fuel Cell Technology" (from left to right).*

BUSINESS AREAS

Silicon Photovoltaics	Dr Stefan Glunz Dr Ralf Preu	+49 761 4588-5191 +49 761 4588-5260
III-V and Concentrator Photovoltaics	Dr Andreas Bett	+49 761 4588-5257
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Photovoltaic Modules and Power Plants	Dr Harry Wirth	+49 761 4588-5858
Solar Thermal Technology	Dr Werner Platzer	+49 761 4588-5983
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Hydrogen and Fuel Cell Technology	Dr Christopher Hebling	+49 761 4588-5195
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Zero-Emission Mobility	Ulf Groos	+49 761 4588-5202
System Integration and Grids – Electricity, Heat, Gas	Prof. Christof Wittwer	+49 761 4588-5115
Energy System Analysis	Dr Thomas Schlegl	+49 761 4588-5473

THE INSTITUTE IN BRIEF

The Fraunhofer Institute for Solar Energy Systems ISE is committed to promoting energy supply systems which are sustainable, economic, safe and socially just. It creates technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. Within its research focusing on energy conversion, energy efficiency, energy distribution and energy storage, the Institute develops materials, components, systems and processes in twelve business areas. Scientific expertise, methods and equipment from eleven fields of competence are applied. In addition to research and development, Fraunhofer ISE also offers testing and certification procedures. Fraunhofer ISE is certified according to DIN EN ISO 9001:2008.

Research and Services Spectrum

The Fraunhofer Institute for Solar Energy Systems ISE is a member of the Fraunhofer-Gesellschaft, the leading organization for applied research in Europe. The Institute finances itself to 90 percent with contracts for applied research, development and high-technology services. Fraunhofer ISE is integrated into a network of national and international cooperation, such as the ForschungsVerbund Erneuerbare Energien (FVEE – German Research Association for Renewable Energy) and the European Renewable Energy Centres (EUREC) Agency.

Networking within Fraunhofer

- Fraunhofer Alliances: Energy, Batteries, Building Innovation, Nanotechnology, Space and Water Systems (SysWater)
- Fraunhofer Electromobility Systems Research Project
- Fraunhofer Group Materials, Components
- Fraunhofer Networks for Electrochemistry, Energy Storage Systems and Grids, Intelligent Energy Grids, Sustainability, Wind Energy
- Fraunhofer Initiative "Morgenstadt – City of the Future"

External Branches and Cooperations

Laboratory and Service Centre, Gelsenkirchen LSC

The Fraunhofer ISE Laboratory and Service Centre LSC, which was founded in 2001 on the initiative and with the continuing support of the State of North Rhine-Westphalia (NRW), specializes in production-relevant process development to manufacture silicon thin-film solar cells, silicon hetero-junction solar cells and multicrystalline silicon solar cells. It has two excellently equipped technological sections and possesses comprehensive measurement facilities to characterize thin films and solar cells.

Fraunhofer Centre for Silicon Photovoltaics CSP

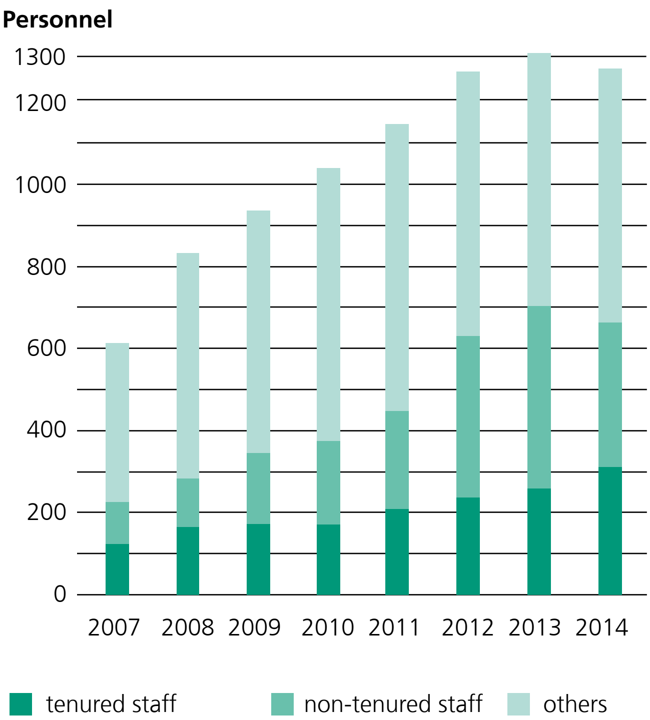
The Fraunhofer Centre for Silicon Photovoltaics CSP in Halle / Saale was jointly founded by the Fraunhofer Institute for Mechanics of Materials IWM, Freiburg and Halle, and Fraunhofer ISE. The central facilities are in the Division "Reliability and Technologies for Grid Parity" (CSP-ZTN) and the "Laboratory for Crystallization Technology" (CSP-LKT). Together with the Silicon Materials Technology and Evaluation Center SIMTEC at Fraunhofer ISE in Freiburg, the latter provides a comprehensive technological platform for industrially relevant crystallization processes applying industrial-type equipment, which goes well beyond the current state of the art.

Technology Centre for Semiconductor Materials THM

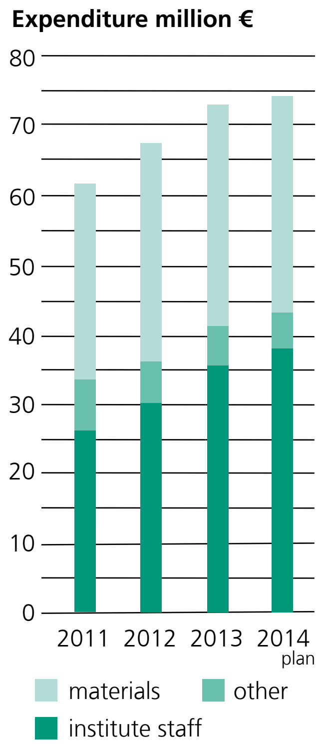
The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, operates in cooperation between Fraunhofer ISE and the Fraunhofer Institute for Integrated Systems and Device Technology IISB in Erlangen. THM supports companies by research and development on materials preparation and processing of 300 mm silicon, solar silicon and III-V semiconductors. In addition, THM offers services in the fields of analytics, characterization and testing.

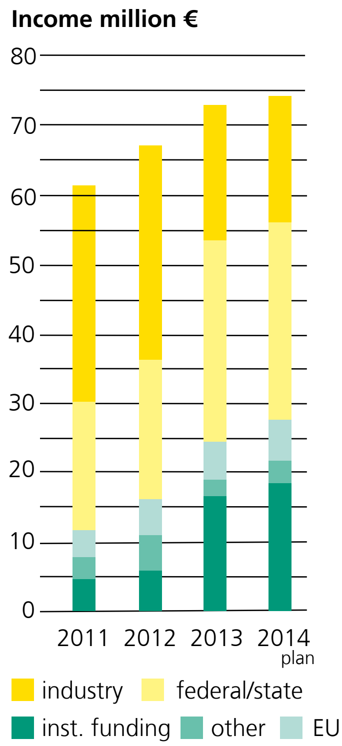
Fraunhofer Center for Sustainable Energy Systems CSE
The Fraunhofer Center for Sustainable Energy Systems CSE in Boston was founded in 2008 as a result of cooperation between Fraunhofer ISE and the Massachusetts Institute of Technology MIT. At Fraunhofer CSE, expertise and technology in the field of renewable energy that is already established in Europe is to be further adapted and introduced to the American market. Together with the Canadian Standards Association (CSA), Fraunhofer CSE is operating a test facility for PV modules, the CFV Solar Test Laboratory, which is located in Albuquerque, New Mexico.

Fraunhofer Chile Research – Centro para Tecnologías en Energía Solar
Fraunhofer has further expanded its activities in Chile by establishing the Centro para Technologías en Energía Solar (Center for Solar Energy Technology). Scientists from the Fraunhofer Institute for Solar Energy Systems ISE, the Pontificia Universidad Católica de Chile and other Chilean universities will conduct research there particularly on the generation of electricity and process heat and on water purification.



On 31st December 2014, a total of 1277 staff members were employed at Fraunhofer ISE. Included in this total are 146 doctoral candidates, 123 diploma / masters students, 42 trainees and 300 scientific assistants as well as 117 other staff members (e. g. guest scientists), who support the research projects with their work and thus contribute significantly to the scientific results obtained.





The financial structure of the Fraunhofer-Gesellschaft distinguishes between 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 2014 our operational budget totalled 74.3 million euros. In addition to the expenditure documented in the graph, the Institute made investments of 11.8 million euros in 2014 (not including investments for building construction and the economic stimulus programme).

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PRIZES AND AWARDS

Fraunhofer Institute for Solar Energy Systems ISE
Zayed Future Energy Prize for the leadership role, example and innovative ability provided by the largest European solar research institute, 20.01.2014, Abu Dhabi, UAE

Arne Hendrik Wienhausen and Andreas Hensel
2nd place, Zukunftspreis 2013 der Stiftung Ewald Marquardt for "Entwicklung eines hocheffizienten, kompakten Resonanzwandlers mit Galliumnitrid (GaN)-Transistoren" (Development of a highly efficient, compact resonance converter with gallium nitride (GaN) transistors), 21.02.2014, Rietheim-Weilheim, Germany

Christian Schöner, David Derix, Andreas Hensel
1st Poster Prize of the Ostbayerisches Technologie-Transfer-Institut e.V. (OTTI) for "Vergleich von verschiedenen Dreipunkt-Topologien für PV-Wechselrichter zur Eigenverbrauchsoptimierung" (Comparison of different three-point topologies for PV inverters for optimization of on-site consumption)
29. Symposium Photovoltaische Solarenergie, 12.–14.03.2014, Bad Staffelstein, Germany

Frank Feldmann, Friedemann Heinz, Florian Schindler, Matthias Breitwieser
SiliconPV Award 2014 for "The 10 Best Ranked Contributions of SiliconPV 2014" 23.–25.03.2014, s-Hertogenbosch, Netherlands

Dr Ralf Preu, Dr Jan Nekarda, Martin Graf
"Innovation Award Laser Technology 2014" of the Arbeitskreis Lasertechnik e.V. and European Laser Institute ELI recognizing the innovation concerning "Laser Fired Contact (LFC) technology for the production of high-efficiency silicon solar cells", 07.05.2014, Aachen, Germany

1 *Prof. Wim Sinke, Program Development Manager, ECN Solar Energy; Prof. Joachim Luther, Chairman of the Becquerel Prize Committee; Vladimir Sucha, Director-General JRC, European Commission; Dr Stefan Glunz, Becquerel Prizewinner in 2014 (from left to right).*
2 *The prizewinning team for the Innovation Award Laser Technology 2014: Martin Graf, Dr Ralf Preu and Dr Jan Nekarda (from left to right), displaying silicon solar cells with laser-contacted aluminium back surfaces prepared by different processes.*

Sarah Röttinger
3rd Prize for OPV Posters for the poster entitled "Outdoor Measurements and Stability on Hybrid Inorganic-Organic Photovoltaics", 14.05.2014, Lausanne, Switzerland

Dr Benjamin Thaidigsmann
KlarText! – Klaus Tschira Prize for Accessible Scientific Writing for "Solarzellen mit Rückspiegel" (Solar cells with rear-vision mirrors), 09.09.2014, Heidelberg, Germany

Maike Wiesenfarth
Poster Prize at ESTC 2014 – 5th Electronics System-Integration Technology Conference for the poster entitled "Challenges for Thermal Management and Production Technologies in Concentrating Photovoltaic (CPV) Modules", 18.09.2014, Helsinki, Finland

Dr Stefan Glunz
22nd Becquerel Prize, recognition by the EU Commission of pioneering work on high-efficiency solar cells, European PV Solar Energy Conference, 22.09.2014, Amsterdam, Netherlands

Dr Marek Miara
The RENERGY AWARD, RENEXPO Poland, Winner in the category "Outstanding Personality in the Field of Renewable Energy and Energy Efficiency", 23.09.2014, Warsaw, Poland

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THE "FRAUNHOFER ZAYED PROGRAMME"

In January 2014, the Fraunhofer Institute for Solar Energy Systems ISE received the Zayed Future Energy Prize, which is awarded annually for innovative and far-reaching performance in the area of renewable energy and sustainability. The Institute Director, Prof. Eicke Weber, accepted the illustrious prize, which is accompanied by 1.5 million US dollars as prize money, on behalf of the Institute from Sheikh Mohammed Bin Zayed Al Nahyan, the Crown Prince of Abu Dhabi, during the Sustainability Week in Abu Dhabi.

1 *Zayed Future Energy Prize 2014 awarded to the Fraunhofer Institute for Solar Energy Systems ISE: Institute Director, Prof. Eicke R. Weber, accepts the Zayed Future Energy Prize 2014, which is accompanied by prize money of 1.5 million US dollars, from Sheikh Mohammed Bin Zayed Al Nahyan, Crown Prince of Abu Dhabi. ©Ryan Carter / Crown Prince Court – Abu Dhabi*

2 *Compact system on Tenerife, Spain.*

Fraunhofer ISE is pleased that the idea for using the prize money, which was expressed during the acceptance speech, can already be implemented in the same year as the award. The guiding motive for beneficial use of the funds was to support countries, which have not yet embarked on an energy transformation, with Fraunhofer research. For example, this could mean that energy system analyzes and supply models for a smooth and cost-effective transformation to a sustainable energy system, which have been developed at Fraunhofer ISE, would be further developed for other regions and form the basis for serious technological cooperation.

Project Funding toward Supplying Sustainable Energy outside Germany

Following the suggestion of Prof. Eicke Weber, the Executive Board of the Fraunhofer-Gesellschaft also authorized further funding equal to the prize money of 1.5 million US dollars (1.089 million euros) for a programme to provide seed funding for Fraunhofer projects on supplying sustainable energy in countries outside Germany. Initiatives for such international projects often founder for lack of funding to establish contacts, make initial visits, provide feasability studies or surmount administrative hurdles during the preparation of grant applications or quotes. The "Fraunhofer Zayed Programme" is intended to make a financial contribution to overcome such difficulties.

Projects that are supported by this programme serve to prepare and acquire international projects in the areas of energy supplies, energy conversion or energy usage. Suitable follow-up projects should contribute to reducing or preventing harmful emissions or to increasing economic feasibility by improving efficiency or introducing new technology or processes. Selection criteria for the projects to be funded within this programme include an increase in knowledge, e. g. by the adaptation or development of new technology, but also sustainability and development, e. g. in accordance with the millennium development goals defined by the United Nations. Sustainability includes aspects of permanence in the solution of urgent local problems, whereby sustainability can also be understood to mean corporate social responsibility. One main criterion for funding is the probability that the seed support is likely to lead to a project with external financing.

FRAUNHOFER ISE ALUMNI

"Fraunhofer ISE ALUMNI – Networking for a Solar Future": This is the motto for the Internet platform which the Institute established in the summer of 2014 for former staff members. The portal was officially opened at the first alumni event, which was held during the 29th European Photovoltaic Solar Energy Conference and Exhibition in Amsterdam. The current Institute Director, Prof. Eicke Weber, together with his two predecessors, the founding Director, Prof. Adolf Goetzberger, and Prof. Joachim Luther, greeted alumni from all over the world, from Sweden, Austria and Poland to the USA. Both the alumni portal and alumni gatherings at conferences and trade fairs aim to promote and strengthen networking not only between former and current Fraunhofer ISE staff but also among the alumni themselves, who can find each other again via the platform.

Great Potential for Fruitful Networking

The largest European solar research institute currently has a staff of 1300 and has a history of more than 30 years, in which it has educated a great number of experts. During the last 20 years alone, 220 doctoral theses have been written. In addition, more than a dozen spin-off companies were initiated directly by Fraunhofer ISE or have been founded by former employees. There is clearly great potential for fruitful alumni activity.

Numerous former employees of Fraunhofer ISE have been attracted away from Freiburg to positions around the world. They are active today in industry, professional associations and interest groups, other research institutions, education, consultancy and politics. In their new positions as competent managers, opinion leaders and decision makers, they determine future structures, influence market development, are responsible for product innovation and often make decisive contributions to the success of an enterprise. Over the years, they have gained much expert knowledge and experience. Most of them have remained faithful to renewable energy – a topic which continues to bind them together following their time at Fraunhofer ISE.

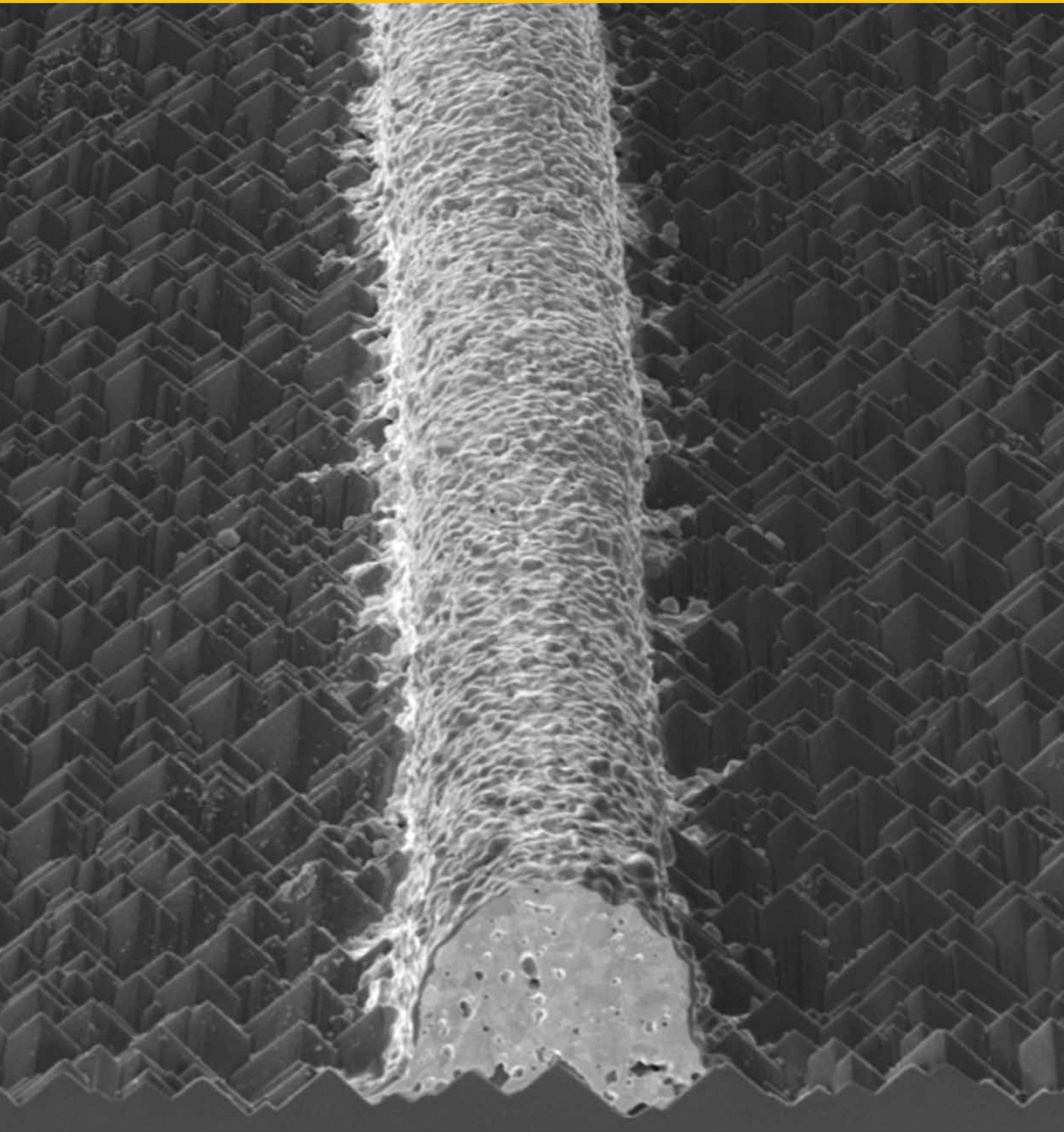
Around 50 former members of staff have already registered via the online Alumni Portal since its launch at the end of September 2014. As a reader of our Annual Report, maybe you are an alumnus or an alumna yourself, or know former employees of Fraunhofer ISE. We would be pleased to gain your support as a multiplier for this network, with its goal of promoting our shared ideal of a sustainable global energy supply.

www.alumni.ise.fraunhofer.de

BOARD OF TRUSTEES

The Board of Trustees assesses the research projects and advises the Institute Directorate and the Board of the Fraunhofer-Gesellschaft with regard to the work programme of Fraunhofer ISE (Status: 31st December 2014).

SILICON PHOTOVOLTAICS



Around 90 % of currently manufactured solar cells are based on crystalline silicon. The efficiency, price-to-performance ratio, long-term stability and potential for further cost reduction indicate that this peak performer in terrestrial photovoltaics will continue to dominate the market in the future. Our R&D spectrum has the goal of cooperation with the industry to introduce new, innovative products to the market. The aim is to reduce manufacturing costs and thus assist the PV industry in Germany and Europe to compete internationally. Our activities mirror the complete value chain for crystalline silicon photovoltaics.

The PV materials platform of Fraunhofer ISE covers all research topics from crystallization to wafers and consists of the following centres: the Silicon Material Technology and Evaluation Centre SIMTEC in Freiburg, the Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, and the Centre for Silicon Photovoltaics CSP in Halle. Our scientific work here focusses on improving the crystallization process to produce silicon crystals as the starting point for highly efficient solar cells, and producing thin wafers with little kerf loss. We are developing specific equipment and processes for the concept of crystalline silicon thin-film solar cells. The work focusses on equipment for high-throughput silicon deposition and appropriate processes to produce substrates, thin films and solar cells.

A central activity of our ETAlab® (ETA = efficiency, technology, analysis) is the development and analysis of high-efficiency solar cell concepts and processes. The goal is to achieve higher efficiency values with cost-effective processes and thus provide the prerequisite for substantial cost reduction in silicon photovoltaics. ETAlab® is equipped with excellent processing infrastructure with well-known technology such as boron and phosphorus diffusion and wet chemistry, as well as new alternatives such as ion implantation. These facilities are all located in a clean-room laboratory with a floor area of 500 m². They have allowed us to set several international records for efficiency and to develop new, pioneering approaches such as passivated contacts. In addition, further laboratory area of 900 m² is available for us to develop effective surface passivation methods, novel metallization and doping procedures, innovative nano-structuring technology and new characterization methods.

In the Photovoltaic Technology Evaluation Centre PV-TEC, with an area of more than 1200 m², we can produce both solar cells with screen-printed contacts, as are common in industry, and also solar cells with high-quality surface passivation on a pilot scale, i. e. with a throughput of more than 100 wafers per hour. For the various types of processing technology, both flexible, semi-automatic equipment and high-rate, fully automatic systems for process development are available. 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 and processes. 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 cooperation partners.

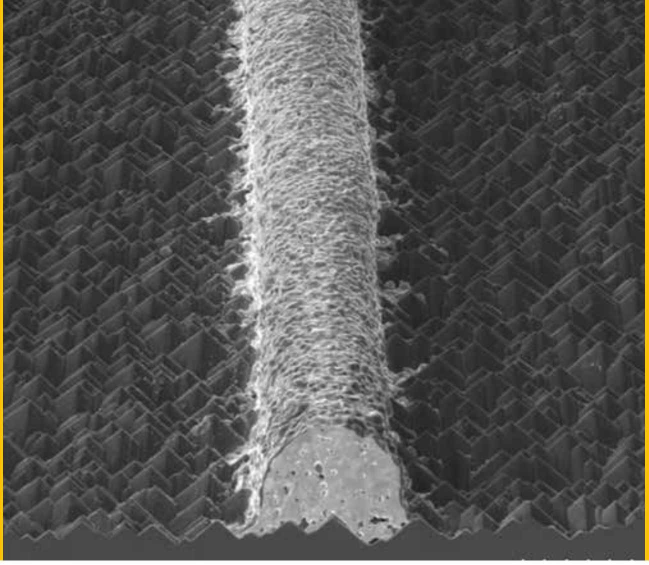
For all of the technological foci mentioned above, our excellent characterization and simulation pool provides the foundation for effective and scientifically based development. We are playing a leading role in the development of new characterization procedures such as the imaging photoluminescence method to analyze silicon material and cells. The Photovoltaic Module Technology Centre Module-TEC 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.

Our activities on silicon material and solar cells in Freiburg are complemented by the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen.

FURTHER INFORMATION

Staff	**350**
Full-time equivalent staff	**253**
Journal articles and contributions to books	**86**
Lectures and conference papers	**117**
Newly granted patents	**12**

www.ise.fraunhofer.de/en/publications/15



Dispensed front-surface contact on a Cz-Si solar cell.

CONTACTS

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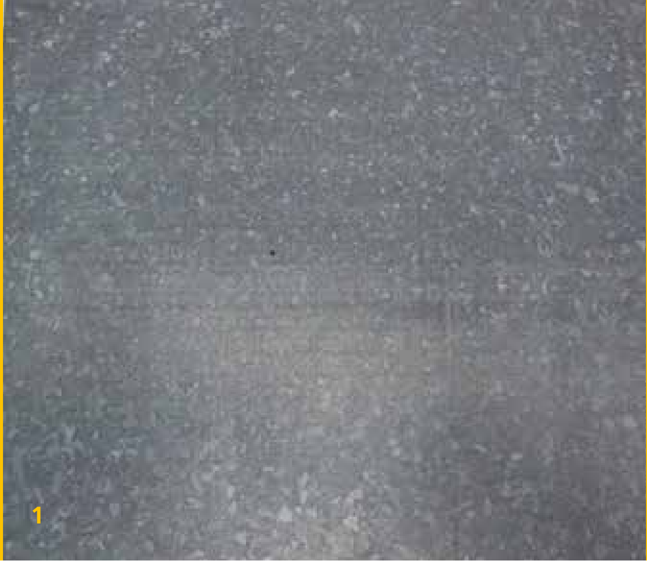

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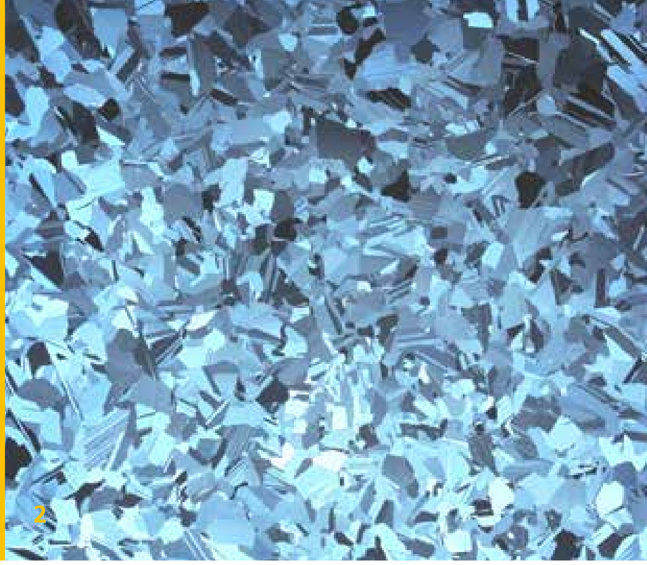

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HIGH-EFFICIENCY MULTICRYSTALLINE SILICON WAFERS FOR PHOTOVOLTAICS

The quality of multicrystalline silicon for PV can be improved by the addition of a fine-grained crystalline structure at the beginning of the growth process. In our research at the Silicon Material Technology and Evaluation Centre SIMTEC on producing "High-Efficiency Multicrystalline Silicon (HE mc-Si)", we are studying the development of crystalline structures and dislocations, particularly dislocation clusters, from initial nucleation to the complete ingot. By deliberately setting the form of the phase boundary during the growth process, and combining this with carefully selected nucleation material, low-defect multicrystalline silicon was produced with very good electrical properties.

Fridolin Haas, Philipp Häuber, Patricia Krenckel,
Stephan Riepe, Claudia Schmid, Andreas Bett

Most crystalline wafer material for solar cells currently consists of multicrystalline p-type silicon. The development of high-quality block material with a very low dislocation concentration (HE mc-Si) has led to significant increases in the efficiency value of the solar cells which have been manufactured from it. The dislocation concentration in the silicon ingot can be reduced by a growth process in which solidification occurs in a stable process that avoids strain in the freshly solidified crystal. A homogeneous grain structure, which begins with very small grains, has proven to be advantageous. During crystallization, smaller grains with often high dislocation concentrations are overgrown by grains with a low dislocation concentration.

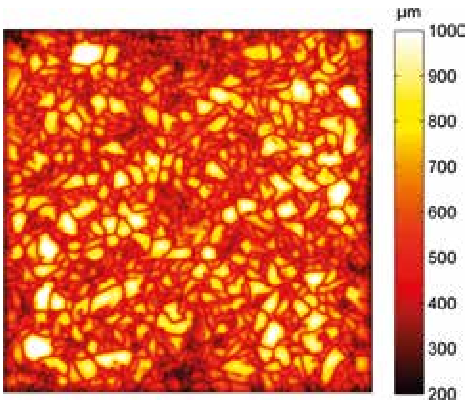
By studying different conditions during the nucleation phase with and without the addition of nucleation material, and by optimizing the crystallization furnace, we have succeeded in producing both p-type and n-type multicrystalline silicon in the G1 ingot size with a very low dislocation density. Throughout the entire height of the ingot, less than 2 % of the area of wafers with an edge length of 156 mm has its quality affected by dislocation clusters.

Fig. 3 shows the diffusion length image of an n-type HE mc-Si wafer after the boron diffusion which is typical for n-type solar cells. The average value determined for the diffusion length is 531 µm and a good number of grains feature diffusion lengths exceeding 950 µm. This is much longer than the thickness of a silicon solar cell, such that the material quality is no longer a limiting factor for the efficiency.

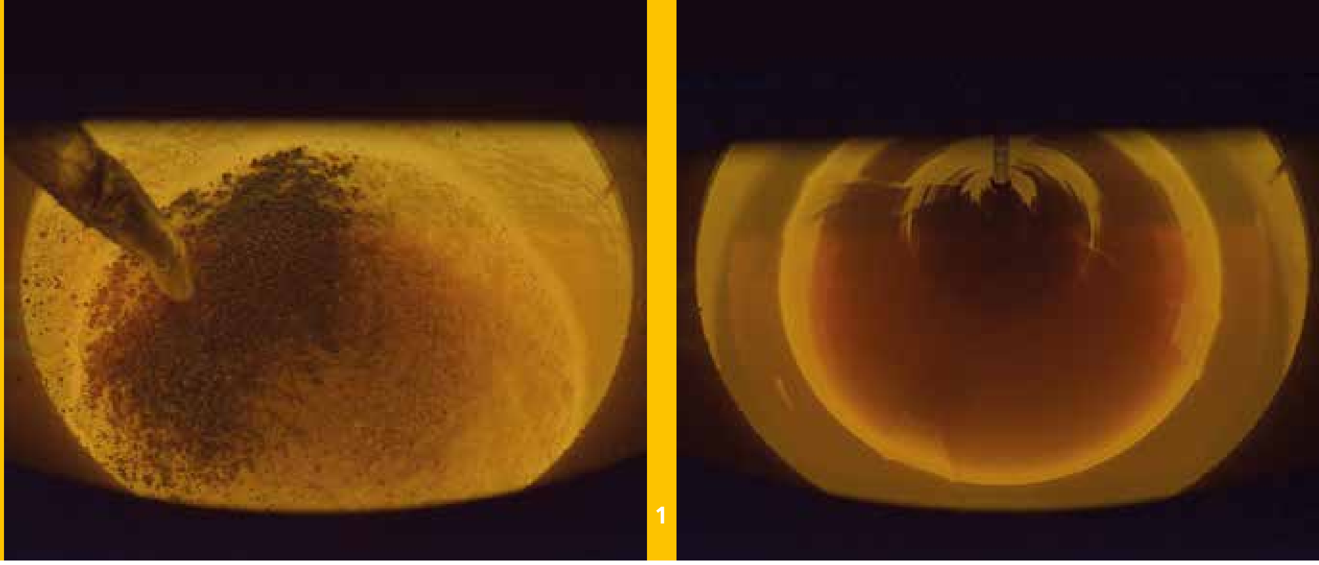
The work is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) in the "THESSO" project.

1 Cross-section of an HE mc-Si ingot near its base with a fine-grained crystalline structure.

2 Wafer with an anti-reflective coating from the cap zone of an HE mc-Si ingot.



3 Diffusion length image of an n-type HE mc-Si wafer after boron diffusion.



COST REDUCTION BY MULTIPLE PULLING IN MONOCRYSTALLINE SILICON PRODUCTION

At present, all monocrystalline wafers for the PV industry are produced with the Czochralski process. In the Cost of Ownership calculation, the cost share for consumables is almost 70 %. In particular, crucible costs (28 %), graphite components (23 %) and electricity (10 %) are significant. If the crucible costs could be reduced by repeated usage, more than 25 % could be saved compared to the current simple batch operation. We have successfully tested the addition of solid polycrystalline silicon in the form of granulate and small chips to the melt. Using the process optimized at Fraunhofer CSP, up to four crystals were pulled from one crucible.

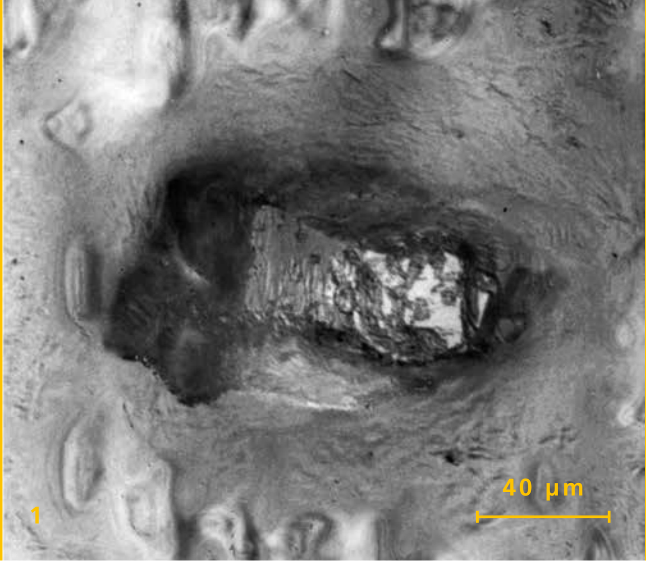
Axel Aderhold, Rainer Barth, **Peter Dold**, Malte Ernst, Roland Kunert, Stefan Wieczorek, Frank Zobel, Andreas Bett

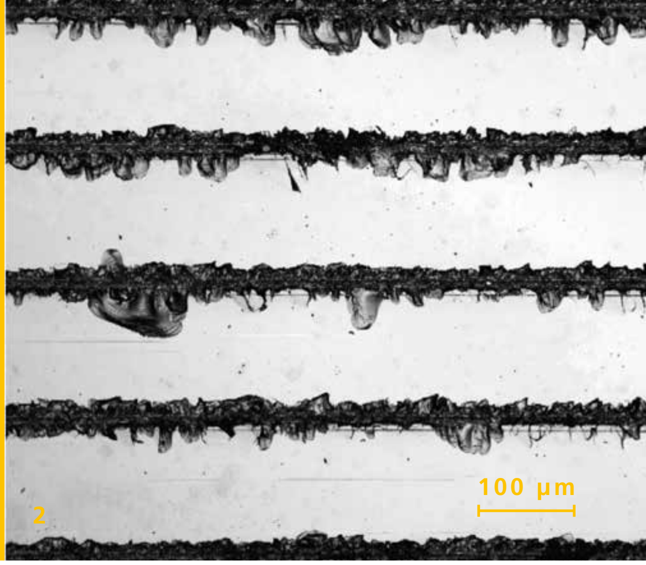
In the Czochralski process, silicon is melted at about 1450 °C in a quartz glass crucible and the silicon crystal is pulled upward out of the melt. Subsequently, the crucible and the remaining melt are cooled down. During cooling, the remaining silicon sticks to the crucible and in addition, the quartz is subject to a phase transition. As a result, the crucible cracks and must be disposed of. With a contribution of 4 to 8 euros per kg of crystallized silicon, the crucibles represent an appreciable cost factor for crystallization. One option for optimization is to add further silicon into the hot crucible, either to improve the filling level at the beginning of the process or to add new material to the remaining melt after completion of one pulling process (Fig. 1). In this way, one or more further crystals can be pulled from the same crucible (multipulling).

We have installed suitable recharging equipment to our Czochralski puller. This allows us to apply the multipulling technique and to analyze its advantages and potential weaknesses. For example, silicon granulate from Fluidized Bed Reactors shows the best pouring characteristics, but trapped processing gases can result in uncontrolled splattering of silicon droplets. This problem is avoided when small fragments of polycrystalline silicon from the Siemens reactor are used. However, there is then a higher risk that the recharging equipment becomes blocked due to the irregular dimensions of the silicon fragments. By modifying the filling pipes and transport mechanism appropriately, we have largely solved this problem.

With these and other process improvements, Fraunhofer CSP is now able to successfully apply multipulling of silicon crystals and provide such material for joint research projects. In addition, we are working on further optimization of the recharging process and the resistance of crucibles to corrosion.

1 *Feeding process, refill of the crucible with polysilicon. In this example, granular poly was fed into the residual melt (left) and an additional 8″ ingot was pulled (right).*





MATERIAL REMOVAL PROCESS OPTIMIZATION WITH NEW SCRATCH TEST STAND

Hard materials are processed mechanically with special tools which must meet strict specifications. These include long tool lifetimes with high removal rates and premium tool surface quality. Investigation and optimization of the removal process and the tool properties are important to achieve these objectives. A test stand developed at Fraunhofer THM enables the removal process as well as the characteristics of abrasive, embedding and operating materials to be investigated cost-effectively, rapidly, precisely and under industrially relevant processing conditions. The optimization of diamond wires to saw PV solar wafers is one of its applications.

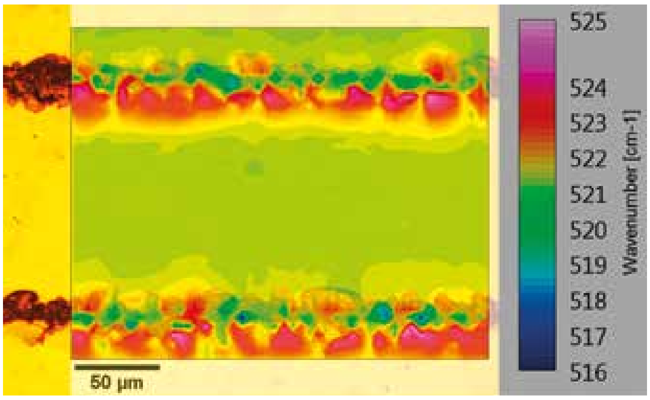
Rajko Buchwald, Hans Joachim Möller, Stefan Retsch, **Sindy Würzner**, Andreas Bett

A high abrasive-particle velocity is the feature of this test stand which is of particular interest for the development of diamond wire for PV silicon wafer production. The test stand allows the industrial removal process to be reproduced in the laboratory. A single abrasive particle or a layer of abrasive grains is fixed onto a grinding wheel and accelerated to 20 m/s. By continuously transporting the test material, we have created individual scratches which can be evaluated in the laboratory by REM and Raman measurements and correlated to the scratching parameters used. This makes it possible to analyze the stress conditions and phase transitions in the silicon material with high resolution. In the centre of the scratch, we detected tensile stresses and transformation of the silicon to a microcrystalline phase (blue regions in Fig. 3). Edge regions which were not chipped showed strong compressive stress, and are visible as magenta zones in the Raman map. By correlating the material removed from the sample to grain abrasion, we predict the tool performance and determine, analyze and optimize the influence of the most important sawing parameters on the removal process. The analytical method is applicable not only to silicon wafering but can also be transferred to other hard materials.

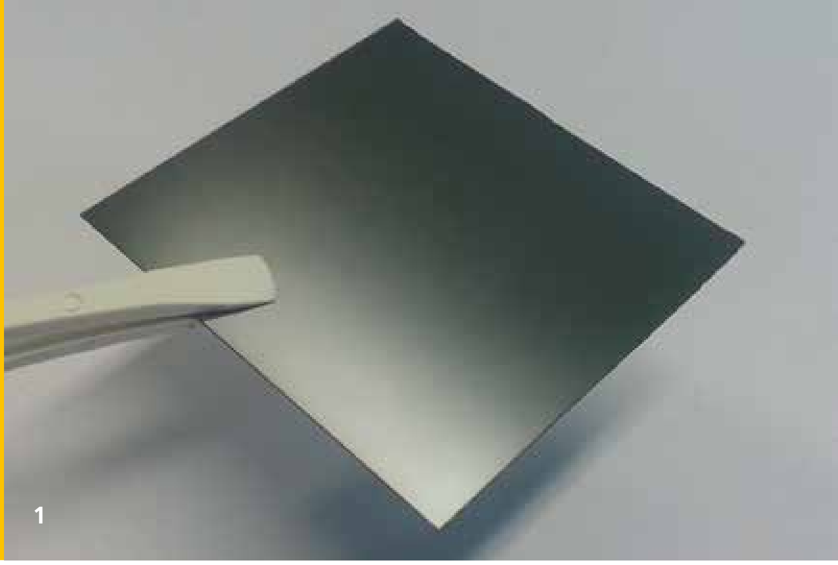
The project was supported by the European Fund for Regional Development (EFRD), the German Federal Ministry for Economic Affairs and Energy (BMWi), the Federal Ministry of Education and Research (BMBF) and the Sächsische Aufbaubank (SAB).

1 *Optical micrograph of an individual diamond grain with an average diameter of 40 µm, which is embedded on the grinding wheel.*

2 *Optical micrograph of the scratch pattern with isolated, periodic scratches on a polished Cz silicon wafer. The geometrical parameters of the scratches were analyzed to determine the removal rate.*



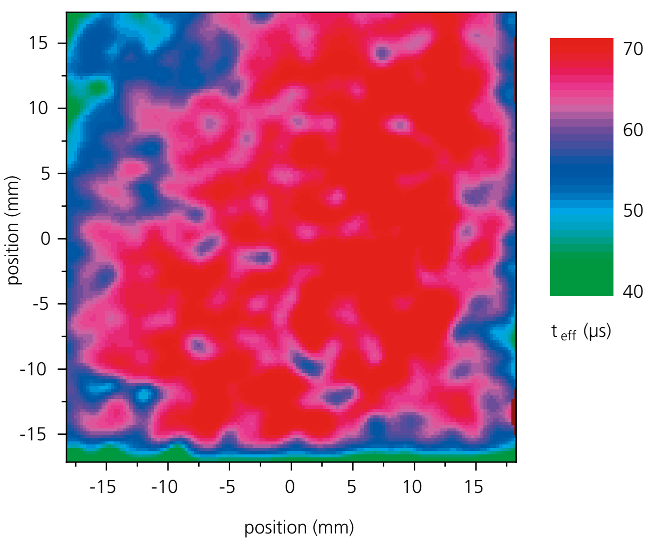
3 *Raman map to analyze material stress by evaluation of the wavenumber shift.*



SILICON FILMS FOR PHOTOVOLTAIC APPLICATIONS

In the production of wafer-based solar cells, the usage of extremely pure silicon represents about one third of the costs. Silicon film technology offers an alternative to producing silicon wafers by sawing. In addition to significantly thinner absorber thickness and smaller material losses in production, this approach also offers more flexibility in the absorber area. We are able to reproduce all of the processes in the value chain, from production of the multi-layer porous silicon coatings up to separation of the extremely thin films. We are concentrating on further developing processes and equipment for larger film areas and higher throughput.

Martin Arnold, Mario Drießen, Elke Gust, **Stefan Janz**, Nena Milenković, Thomas Rachow, Stefan Reber, Kai Schillinger, Andreas Bett



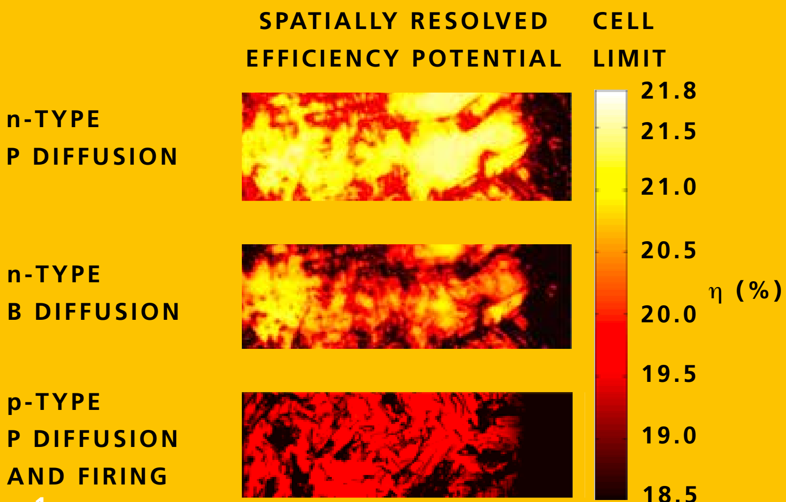
2 *Spatially resolved distribution of minority charge carrier lifetimes over a self-supporting Si film with a thickness of 30 µm after wet-chemical cleaning and passivation of both surfaces with aluminium oxide, measured with the microwave photoconductance method.*

1 *Thin silicon film (30 µm), produced by electrochemical porosification of a wafer, reorganization in a hydrogen atmosphere, epitaxy and subsequent vacuum-assisted separation.*

We develop processes and technology to produce thin silicon films for solar cells with potential efficiency values exceeding 20 %. Electrochemical porosification of a monocrystalline silicon crystal is the process we apply with in-line equipment for wafer areas of 156 mm x 156 mm and larger, to produce films with a thickness of a few tens of micrometres. The resulting crystalline template is subsequently reorganized and epitaxially thickened in the ProConCVD atmospheric-pressure CVD reactor. This was developed for sample sizes of up to 500 mm x 500 mm. The thin Si film with a thickness of 30 to 50 µm is then separated from the substrate with a vacuum-assisted separation unit. To produce solar cells, we then either transfer the flexible films onto a ceramic substrate or process them further as self-supporting films (Fig. 1). To determine the material quality, the films are cleaned by wet-chemical methods, passivated on both sides and subsequently measured with the microwave photoconductance (µ-PCD) method (Fig. 2).

We offer our clients comprehensive routine and development services concerning all process steps: Substrate selection, porosification or implantation, annealing and reorganization of the porous layer stack, epitaxial deposition on reorganized porous layers, separation and diverse procedures to transfer the films to inexpensive substrates, and adapted solar cell processes.

The project is supported by internal funding and the German Federal Ministry for Economic Affairs and Energy (BMWi).



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POTENTIAL ANALYSIS OF MULTICRYSTALLINE n-TYPE SILICON

Monocrystalline n-type silicon is becoming increasingly common in solar cell production, particularly in the high-efficiency sector. By avoiding the harmful boron-oxygen defect and with its lower sensitivity to most metallic impurities, n-type silicon has advantages compared to boron-doped p-type silicon. Although the efficiency potential for multicrystalline (mc) silicon is lower than for monocrystalline silicon, the former material is significantly less expensive to produce. We analyzed the efficiency potential of mc n-type silicon in comparison to p-type silicon. Because special silicon blocks were used, that were crystallized identically for n-type and p-type material, the comparative study is very informative.

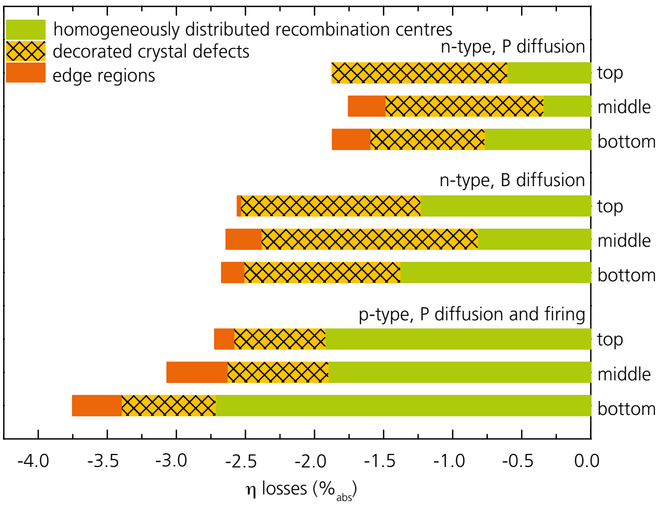
Bernhard Michl, Stephan Riepe, **Florian Schindler**,
Jonas Schön, Martin Schubert, Wilhelm Warta, Stefan Glunz

Different typical solar cell processes were applied to p-type and n-type wafers that had been cut in parallel at various block heights: boron diffusion (for n-type PassDop cells), phosphorus diffusion and phosphorus diffusion with a firing step (for p-type PERC cells). The limitation of solar cell properties due to the material was determined by spatially resolved and injection-dependent lifetime measurements on the passivated wafers and Efficiency-Limiting Bulk Recombination Analysis (ELBA) (Fig. 1). Despite the lower mobility of holes, the measured diffusion lengths in mc n-type material are clearly higher than in p-type material. For the analyzed cell concepts, the upper limits to the efficiency value which are determined by the material are higher on average for the n-type block compared to the p-type block by +0.7 $\%_{abs}$ (after B diffusion) and +1.5 $\%_{abs}$ (after P diffusion).

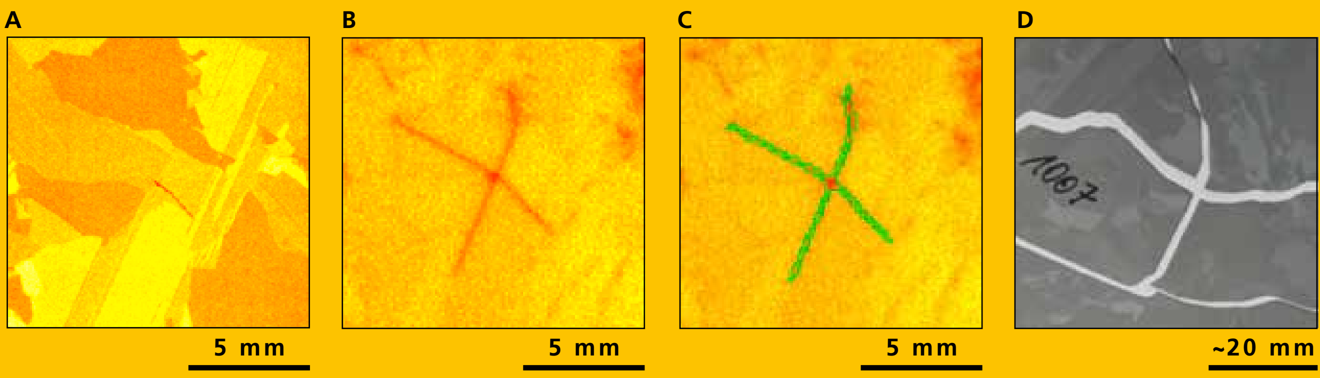
The ELBA method also allows us to identify the causes of losses (Fig. 2). The higher efficiency potential for high-efficiency cells of mc n-type silicon are primarily due to the greater tolerance to recombination centres that are distributed homogeneously within the grains. The losses due to the material in conventionally produced mc n-type blocks are mainly caused by decorated grain boundaries and dislocations; their influence is strongly reduced by the new production procedure for "high-performance multi". In this way, the efficiency potential of mc n-type high-efficiency cells could be increased further.

The work is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the "THESSO" project.

1 *The efficiency potential which is determined from lifetime measurements is significantly higher for the processed n-type wafers than for comparable p-type wafers. The largest differences are found in good grains.*



2 *ELBA analysis of losses caused by the material for differently processed n-type and p-type wafers from various block heights.*



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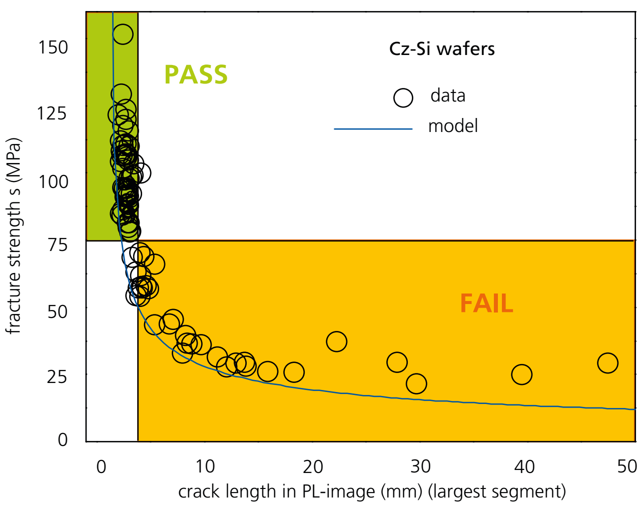
MICRO-CRACKS IN WAFERS AND CELLS: DETECTION AND CLASSIFICATION

As micro-cracks in wafers can lead to wafer fracture and short circuits in the cell, efficient micro-crack detection is decisive in increasing the yield from a production line. Although infrared (IR) transmission and photoluminescence (PL) methods have been implemented in commercially available in-line measurement systems, micro-crack detection is often not applied consistently. The main reason is that up to now, robust classification criteria have been lacking and the detection accuracy of the algorithms used has been limited. We have applied machine-learning processes to develop a robust detection algorithm and evaluation criteria, which allow critical monocrystalline (Cz-Si) and multicrystalline (mc-Si) wafers to be identified reliably.

Matthias Demant, Sebastian Nold, **Stefan Rein**, Ralf Preu



2 *Correlation between the fracture strength of monocrystalline wafers and crack length in comparison to an analytical model and corresponding classification criteria: To achieve the minimum required fracture strength of 75 MPa, wafers with cracks longer than 3.5 mm must be rejected.*

1 *Micro-crack in a multicrystalline wafer: (a) IR image, PL images (b) before and (c) after application of the crack detection algorithm, (d) the broken wafer after a bending test.*

As can be seen in Fig. 1, the detection of micro-cracks in mc-Si wafers presents a challenge, as other defects such as grain boundaries create interfering contrasts of similar appearance. To improve detection, algorithms were developed, which take account of the crack structure during identification. The algorithms were trained according to learning procedures on an extensive set of samples with artificially created cracks. With this approach, a precision of up to 91 % and a recognition rate of up to 80 % were achieved for PL images, despite interfering contrasts. Although the detection of micro-cracks in IR images is easier due to greater contrast differences between those originating from cracks and other causes, the PL analysis is quantitatively more accurate, because the full extent of cracks is often not evident in IR images, as Fig. 1a and 1b illustrate. The algorithm developed can improve the detection quality, regardless of the type of measurement technology used.

The fracture strength must be estimated from the detected crack configuration in order to evaluate the micro-cracks reliably. The fracture strength of the investigated wafers was determined in a 4-bar bending test. Fig. 2 shows that the strength in Cz-Si wafers decreases systematically with increasing crack length, which is well described by an analytical model of the fracture mechanics and allows sharp sorting criteria to be defined. The correlation for mc-Si wafers is not as sharp but still allows very poor wafers to be identified.

The "xµ-Zellen-2" project was supported by the German Federal Ministry of Education and Research (BMBF).

THICKNESS DETERMINATION OF DIELECTRIC LAYER STACKS FOR IN-LINE APPLICATIONS

The PERC concept (Passivated Emitter and Rear Cell) is a promising approach to increase the efficiency of solar cells and involves coating the back surface of a solar cell, typically with two thin dielectric layers. The layer thickness affects the electrical and optical properties of these solar cells. The usual method to characterize the layers is ellipsometry. At Fraunhofer ISE, a procedure based on spectral reflectance was developed which, in contrast to ellipsometry, allows the thickness of double-layer thin-film stacks to be determined reliably also on slightly micro-rough surfaces and during a running solar cell production process.

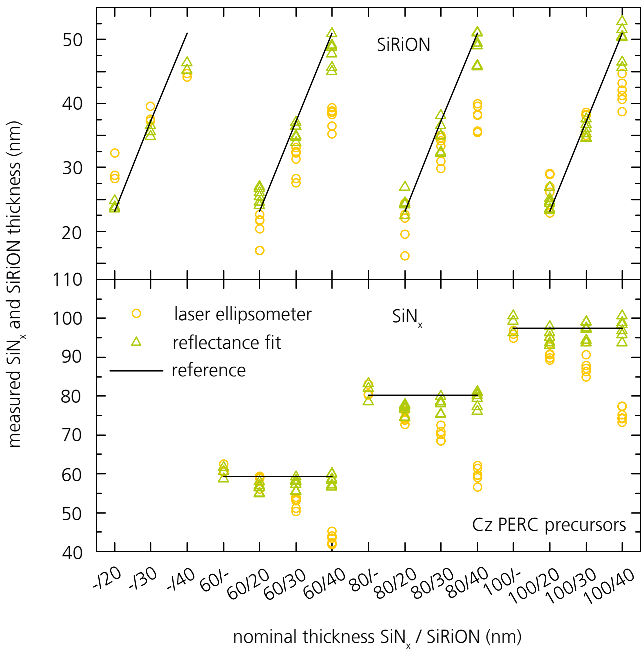
Johannes Greulich, Alexander Krieg, Stefan Rein, Nico Wöhrle, Ralf Preu

The spectral reflectance of the back surface of PERC solar cell precursors depends essentially on the refractive indices and thicknesses of the deposited dielectric films and can be calculated from these data. This relationship can be used to determine the film thicknesses by fitting the simulated reflectance R_{sim} to the reflectance R_m measured after film deposition. In the calculation, the refractive indices are assumed to be known and the thickness of both dielectrics is varied until the best fit of R_{sim} to R_m is obtained.

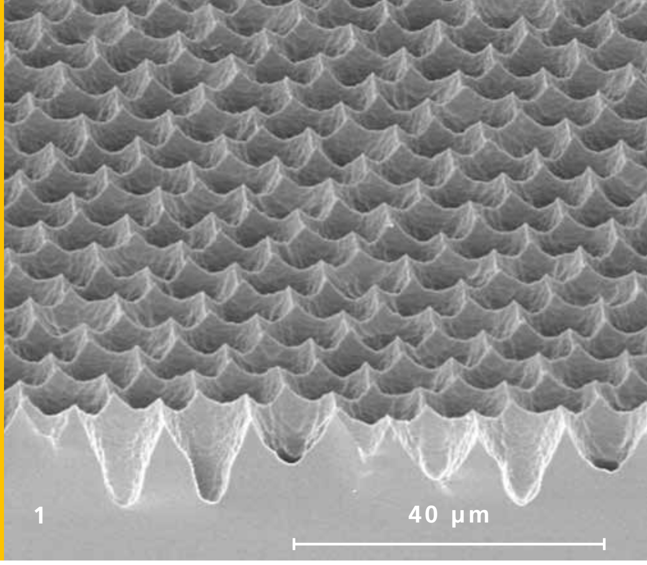
The method was tested with PERC solar cell precursors. These feature double layers of differing thickness consisting of silicon-rich silicon oxynitride (SiRiON) and silicon nitride (SiN_x) (Fig. 2). The film thicknesses were determined with a laser ellipsometer and with the curve-fitting procedure from the spectral reflectance. Reference measurements of single coatings deposited on flat samples were made with a spectral ellipsometer. The thickness values determined with the laser ellipsometer deviate systematically to lower (SiN_x) or higher (SiRiON) values, whereas the reflectance-based procedure displays higher accuracy without systematic deviations (Fig. 2). It is thus well suited for determining the thickness of thin coating stacks on PERC solar cells in-line during a running production process.

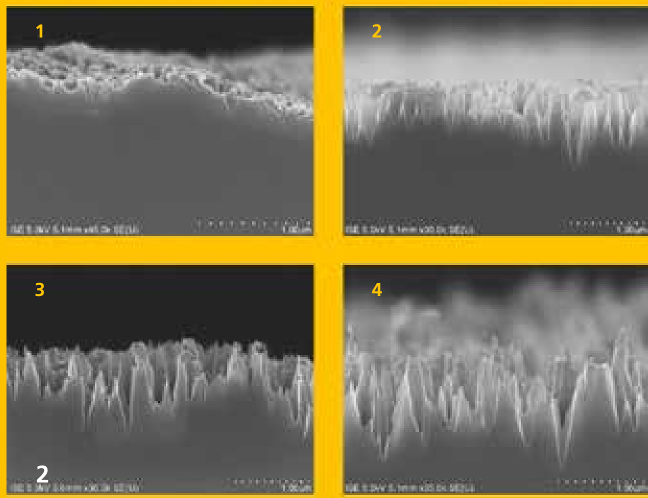
The project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) in the "QUASSIM-PLUS" project.

1 *Back surface of a PERC solar cell precursor with a double-layer coating. Its reflectance properties can be used to determine the thickness of the individual layers in-line during production.*



2 *The layer thicknesses determined from reflectance spectra for double-coated PERC precursors agree significantly better with the reference values (from spectral ellipsometry of flat samples with single coatings) than those determined by laser ellipsometry.*

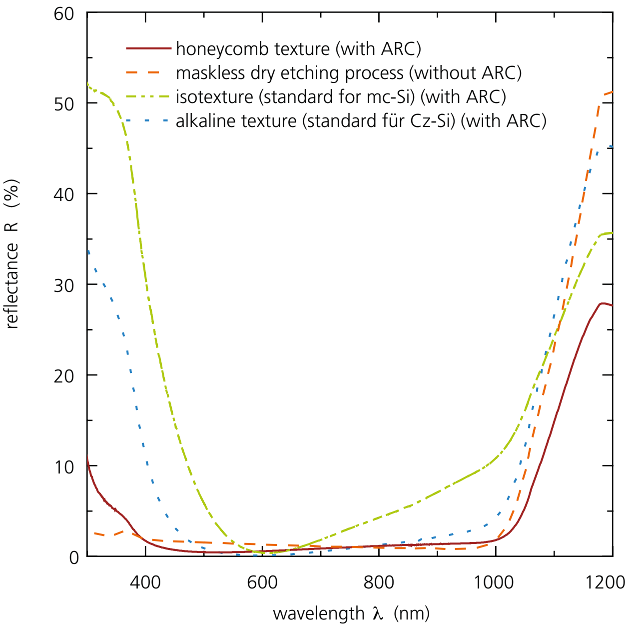




EFFECTIVE ANTI-REFLECTIVE TEXTURE FOR MULTICRYSTALLINE SURFACES

The efficiency of multicrystalline silicon solar cells can be increased by an improved front surface texture which optimizes the reflection properties. Micrometre-scale honeycomb structures were already applied to mc-Si material for the world record solar cell from Fraunhofer ISE. This technology can now be implemented industrially using the processes presented here. Nano-scale "black silicon" textures enable still lower reflectance values of less than 5 %. Fraunhofer ISE used both technological procedures to produce solar cells with higher efficiency values.

Benedikt Bläsi, **Hubert Hauser, Marc Hofmann**, Bishal Kafle, Jochen Rentsch, Daniel Trogus, Nico Tucher, Anne-Kristin Volk, **Martin Zimmer**, Ralf Preu



3 *Reflectance of Si surfaces with different textures. Only the "black silicon" texture achieves very low reflectance values without an anti-reflective coating (ARC).*

1 *Honeycomb surface structure of a crystalline silicon wafer. All the processes used were developed on high-throughput equipment.*
2 *Nano-scale "black silicon" texture. The images are numbered in yellow in the same order as increasing depth of the etched structures. The weighted reflectance decreases in the same order.*

Although multicrystalline silicon solar cells have a lower efficiency value than monocrystalline silicon solar cells, they represent the largest share of the global market due to the lower production price. The difference in efficiency can be significantly reduced by an improved front-surface texturing technology for multicrystalline solar cells. This was demonstrated by the world record for multicrystalline solar cells which Fraunhofer ISE achieved in 2004 for small-area cells. We have now produced the honeycomb texture with process technology capable of high throughput. To do this, large-area nano-imprint lithography, plasma etching and wet-chemical etching were combined to achieve low reflectance values and a high efficiency potential. Efficiency values of up to 17.8 % were achieved for the large-area solar cells of industrial dimensions (156 mm x 156 mm), which means an increase in efficiency of 0.5 $\%_{abs}$ compared to the reference process.

As an alternative, we have cooperated with partners to develop a maskless, dry etching process for texturing, in which climate-friendly F_2 gas was used and which allows very compact equipment dimensions due to its operation at atmospheric pressure without a plasma. Very slight Si ablation with a thickness of 0.5 µm to 1.6 µm leads to very low weighted reflectance values of less than 5 %.

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

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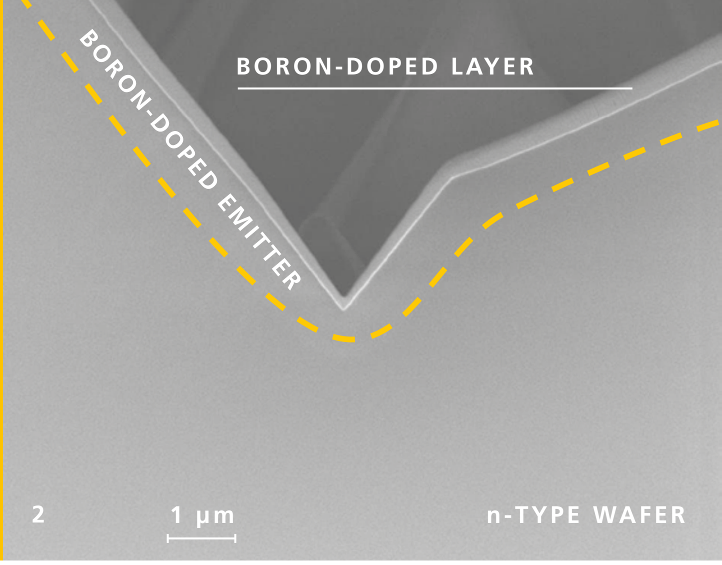

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$POCl_3$-BASED CO-DIFFUSION PROCESSES FOR n-TYPE SI SOLAR CELLS

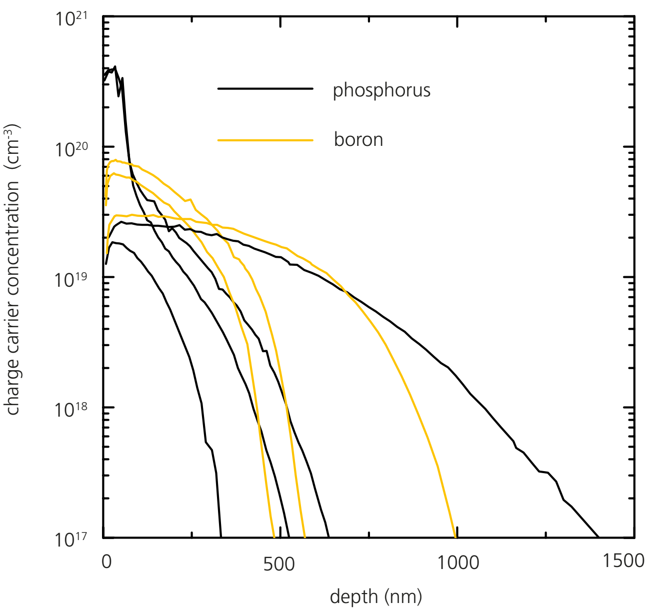
One possibility to further increase the efficiency of Si solar cells is to use n-doped silicon, e. g. in bi-facial solar cell structures (Fig. 1) or rear-contact solar cells. These n-type solar cells often feature two or more differently doped regions. To reduce costs, co-diffusion processes can be used in which the required doped regions are created in a single high-temperature step. Co-diffusion processes were developed at Fraunhofer ISE for bi-facial solar cells and rear-contact solar cells which are based on the use of conventional, widespread $POCl_3$ tube furnace technology. This should make it simple to introduce them to the market.

Daniel Biro, Roman Keding, Sebastian Meier, Philip Rothhardt, **Andreas Wolf**, Ralf Preu

Fraunhofer ISE aims to apply equipment which is already used for production in its further development of industrially relevant diffusion processes. Now, several regions doped with boron and phosphorus can be created simultaneously in a single processing step. For bi-facial solar cells, this is done by depositing a boron-doped oxide layer on one surface of the wafer. For rear-contact solar cells, initially a phosphorus-doped layer is deposited on the back of the cell and structured, followed by deposition of the boron-doped layer. In both cases, the subsequent diffusion occurs in a conventional quartz tube furnace. The previously deposited dopant sources serve to create the boron-doped emitter (Fig. 2) and – for rear-contact cells – also the phosphorus-doped back surface field. At the same time, phosphorus from the gas phase containing $POCl_3$ diffuses into the uncoated side of the wafer. In this way, the phosphorus-doped back surface field of the bi-facial solar cell or the lightly phosphorus-doped front surface of the rear-contact solar cell is created. With our co-diffusion processes, a great variety of doping profiles can be produced effectively independently of each other (Fig. 3). This type of bi-facial solar cell reaches efficiency values of 19.9 % (n-type Cz-Si wafer, 156 mm edge length). Small-scale rear-contact cells achieve efficiency values of up to 21.6 % (n-type Cz-Si wafer, 4 cm² aperture area).

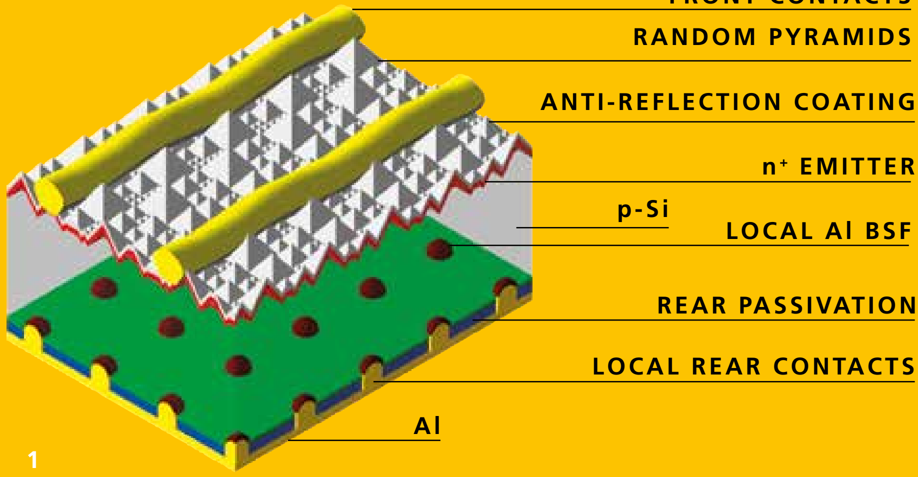
1 *Front (left) and back (right) of a bi-facial n-type Si solar cell.*

2 *Scanning electron micrograph of a cross-sectional fracture, showing the boron-doped layer and the boron-doped emitter created by co-diffusion.*



3 *Various phosphorus und boron doping profiles created in co-diffusion processes.*

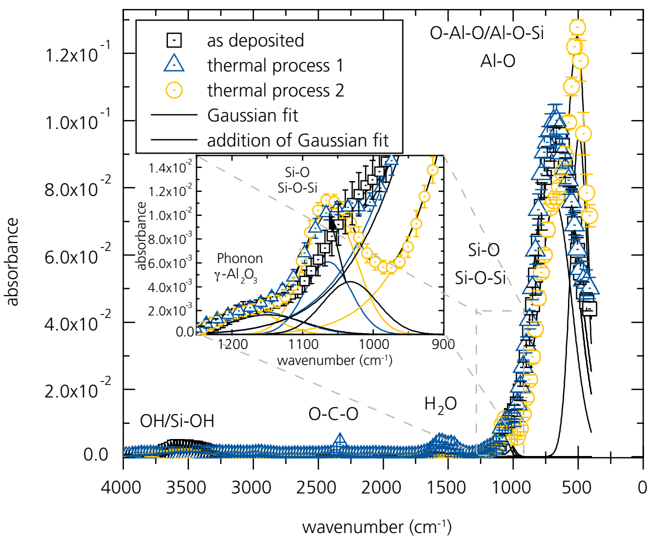
This work is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and the European Union within the "HERCULES" project.



CHARACTERIZATION OF ALUMINIUM OXIDE PASSIVATION LAYERS

The efficiency value of crystalline silicon solar cells is significantly increased by efficient surface passivation. In particular, thin aluminium oxide (Al_2O_3) layers are very suitable for surface passivation and are increasingly being used by the industry. The characterization of Al_2O_3 layers from e. g. different processing conditions is essential for the development of efficient and robust industrial Al_2O_3 deposition processes. Fraunhofer ISE is equipped for a great variety of characterization procedures which allow optical, structural or electrical properties to be investigated.

Jonas Haunschild, Hannes Höffler, **Marc Hofmann**, Saskia Kühnhold, Pierre Saint-Cast, Dirk Wagenmann, Ralf Preu



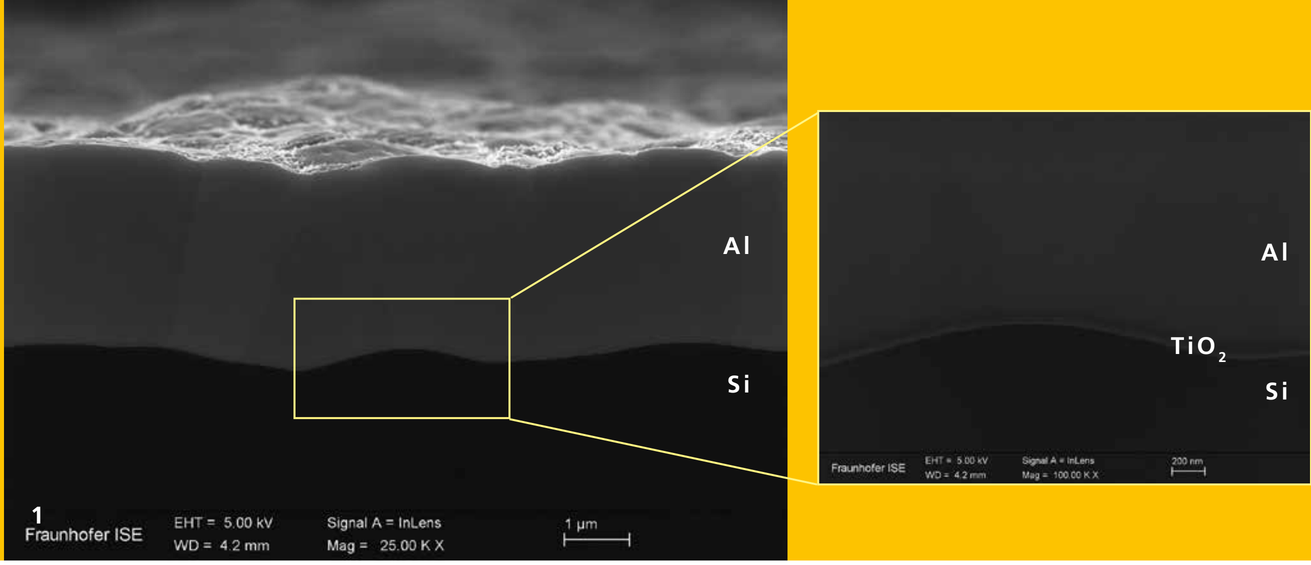
2 *Dependence of the interfacial density of states D_{it} and the oxide charge density Q_{tot} on the thickness of the Al_2O_3 coating produced by PECVD. Al_2O_3 layers are activated by annealing (~425 °C) or firing (~800 °C) processes.*

1 *Structure of a PERC solar cell.*

The highly efficient PERC (Passivated Emitter and Rear Cell) solar cell is being produced increasingly on an industrial scale. An Al_2O_3 passivation layer is usually an essential feature to increase the efficiency of the solar cells. At Fraunhofer ISE, the first industrially applicable Al_2O_3 deposition process was developed. The thickness of the Al_2O_3 passivation layer is a few tens of nanometres. The interface to the c-Si substrate and the properties of the Al_2O_3 bulk play a decisive role for the passivation effect.

The electrical quality of the passivation can be investigated by charge carrier lifetime measurement methods such as QSSPC (Quasi-Steady State Photoconductance) or MW-PCD (Microwave Photoconductance Decay); photoluminescence procedures are particularly suitable to determine their spatial distribution. Interfacial and field-effect passivation properties can be quantitatively investigated by Capacitance-Voltage (CV) or Corona Oxide Characterization of Semiconductor (COCOS) measurements. The optical properties of the passivation layer can be characterized by spectroscopic ellipsometry, and chemical bonding densities by Fourier Transform Infrared Spectroscopy (FTIR).

Fraunhofer ISE has many additional characterization options available, which can be applied when needed. Our staff, with experience in both process development and thin-film characterization, is well equipped to efficiently recognize potential deposition problems and develop appropriate solutions.



CAPPING LAYER FOR PASSIVATION FILMS PRODUCED BY SPRAY PYROLYSIS

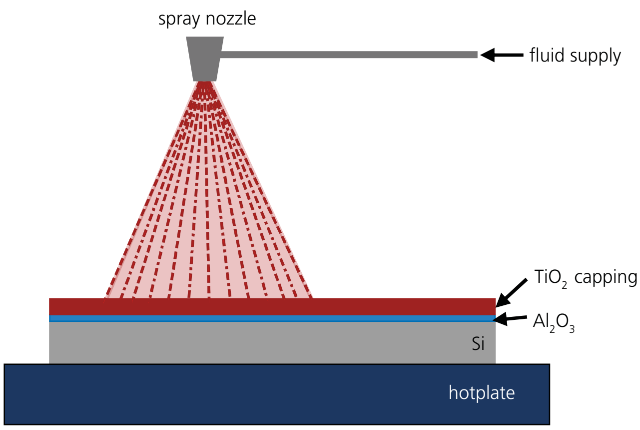
Atomic layer deposition (ALD) of Al_2O_3 is a promising passivation method for high-efficiency solar cell structures. However, the deposition rate is low and the passivation properties are affected by the subsequent metallization processes. Thus, it is useful to work with a coating stack to separate the specifications regarding passivation and the optical or diffusion-barrier properties. It is then possible to create a thin Al_2O_3 layer and subsequently to deposit onto it a suitable capping layer, which has good optical and protective properties and can be inexpensively produced with wet-chemical processes. Metal oxides which can be deposited as sol gels by spray pyrolysis represent an interesting option for this purpose.

Christoph Fleischmann, Markus Glatthaar, **Sybille Hopman**, Wilhelm Hördt, Martin Lieder, Henning Nagel, Stefan Glunz

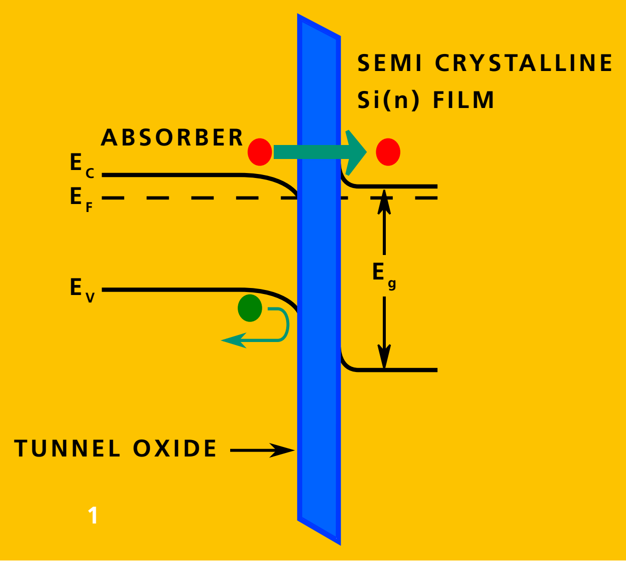
A sol gel is a colloidal dispersion of precursors (usually metal alcoholates) in organic solvents. As there are many possible precursors which could be used as a sol gel for this type of multi-layer stack, the optimal capping stack must be found for each specific application. The process of creating a capping layer by spray pyrolysis is shown schematically in Fig. 2. Depending on the precursor used, the desired dielectric coating can be deposited. The charge carrier lifetimes of the layer are then investigated, and the layer is optimized with respect to its use as an electrical insulation layer, its behaviour during ablation and firing processes and its optical properties. A capping layer must be free of pinholes so that no contact is possible between the metal contact grid and the silicon. In addition, interactions between the capping layer and metals during the firing process are prohibited, i. e. it must also function as a diffusion barrier. Scanning electron micrographs show the homogeneous deposition of this TiO_2 layer on a hot silicon substrate by spray pyrolysis (Fig. 1). The thickness of the deposited TiO_2 layer shown here is about 40 nm.

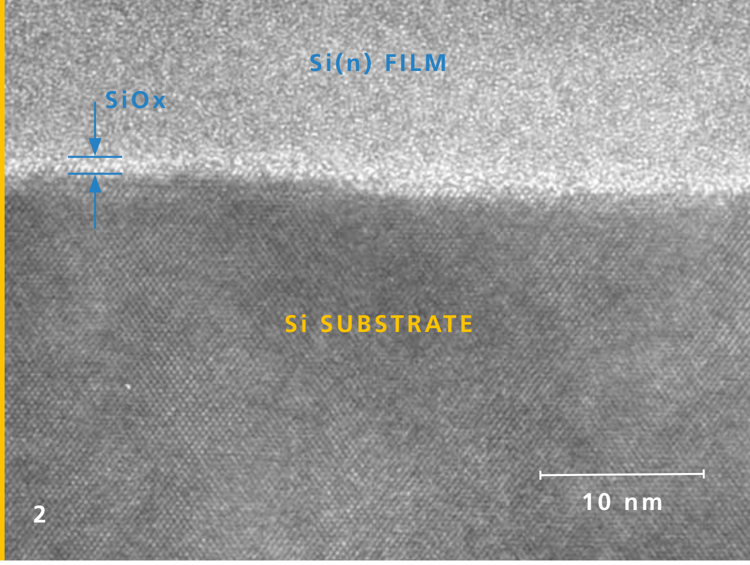
Lifetime investigations of silicon samples with an ALD Al_2O_3 coating and a TiO_2 capping layer, which was deposited as a sol gel by spray pyrolysis, have shown good results up to now. After metallization and the subsequent firing step, the lifetime remained at the same good level, so that we foresee promising opportunities for this technology in solar cell production.

1 *Scanning electron micrograph of a silicon wafer with a TiO_2 coating and aluminium metallization. The image shows a homogeneous TiO_2 coating with a thickness of 40 nm, despite the uneven surface morphology.*



2 *Schematic representation of spray pyrolysis: The silicon wafer lies on a hotplate. The TiO_2 sol gel is sprayed through a nozzle onto the hot surface. The solvent evaporates and the organic components are burnt away.*





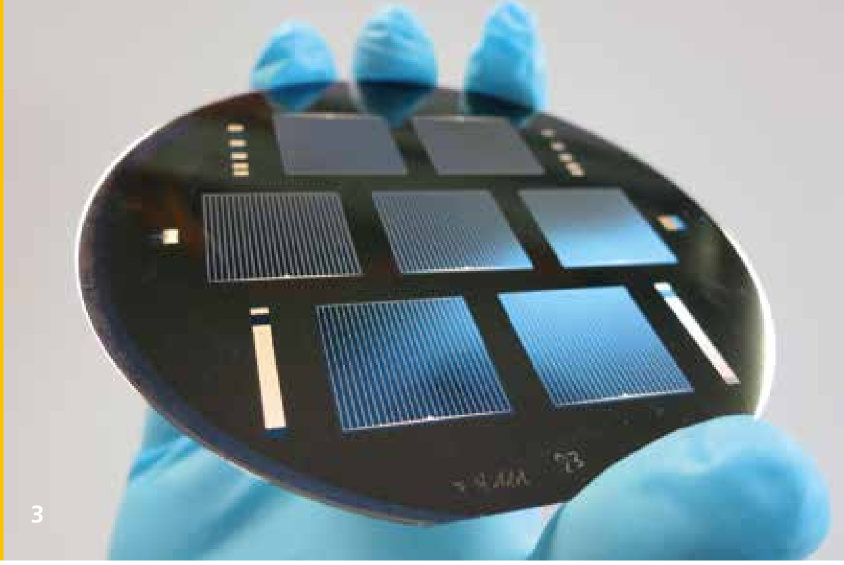
TUNNEL OXIDES FOR HIGHLY EFFICIENT, PASSIVATED CONTACTS (TOPCON)

Selective contacts for different types of charge carriers are a prerequisite for the highest solar cell efficiency. The heart of the passivated TOPCon contact, which was developed at Fraunhofer ISE, is an extremely thin tunnel oxide, which passivates the silicon surface and simultaneously allows almost loss-free current transport. By applying an alternative oxidation procedure based on UV radiators, the quality of the tunnel oxide was improved and cost-effective process technology was identified for industrial production of the TOPCon contact.

Jan Benick, Martin Bivour, **Frank Feldmann**, Martin Hermle, Laurent Kroely, Antonio Leimenstoll, **Anamaria Moldovan**, Christian Reichel, Jochen Rentsch, Felix Schätzle, Christian Schetter, Sonja Seitz, Harald Steidl, Nadine Weber, Martin Zimmer, Karin Zimmermann, Ralf Preu, Stefan Glunz

To increase the efficiency value of silicon solar cells, it is becoming increasingly important to reduce recombination losses, particularly at metal / semiconductor contacts. One possibility is to reduce the contact area to small contact points and to passivate the remaining surface area with a dielectric layer. This so-called PERC concept (Passivated Emitter and Rear Cell) is currently being successfully implemented in the solar cell industry. The disadvantage of this approach is the necessary local structuring of the back surface, which is accompanied by the need for a further processing step and also lengthens the current path within the wafer, which in turn causes resistance losses in the solar cell. The application of continuous selective contacts (passivated contacts) over the whole surface could avoid these disadvantages and lead to higher efficiency values.

The Tunnel Oxide Passivated Contact (TOPCon), which was developed at Fraunhofer ISE, is based on an extremely thin tunnel oxide and a thin silicon layer, which enables excellent charge carrier selectivity due to its larger band gap. The tunnel oxide layer is crucial for the quality of the TOPCon contact. The specifications for this layer are very stringent, as it must both suppress recombination of minority charge carriers and also enable almost loss-free transport of majority charge carriers. In addition, the oxide must not degrade during the subsequent annealing process for the silicon layer. The process takes place at temperatures between 700 and 900 °C and determines important properties such as surface passivation quality and contact resistance. Furthermore, very high annealing temperatures around 900 °C lead to partial crystallization of the silicon layer. This improves the optical transparency of the layers and permits the application of TOPCon on the front surface of the solar cell. However, such high annealing temperatures can also cause decomposition of the tunnel oxide and thus depassivation of the surface. During the current development work, not only the standard wet-chemical oxidation route but also the approach of dry oxidation using UV radiators was evaluated, which offers a cost-effective and elegant alternative. An excimer radiator was used, which emits monochromatic radiation at a wave-



length of 172 nm. This induces the dissocation of molecular oxygen and creates atomic oxygen and ozone as strongly oxidizing species for the oxidation reaction. In comparison to the standard wet-chemical process, the dry UV/O_3 oxidation enables better passivation properties, particularly for samples with textured surfaces and when elevated temperatures are applied during the annealing of the heavily doped silicon layer. Thus, the UV/O_3 oxidation not only improves the passivation by the TOPCon contact but also allows it to be used on the front surface of a solar cell.

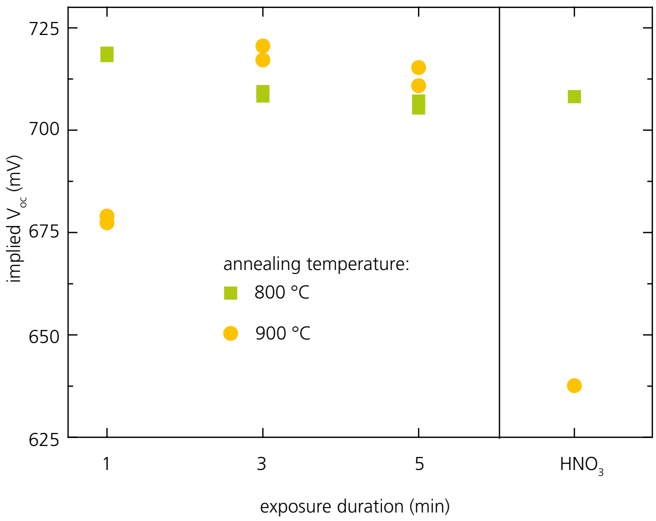
Analysis of the tunnel oxide stoichiometry by X-ray photoelectron spectroscopy (XPS) shows that the oxides grown by the dry-chemical route possess a higher proportion of oxide-rich sub-oxide species, which closely resemble the structure of stoichiometric SiO_2. This supports the assumption that the greater stability during the annealing step is because the oxide layer does not decompose as readily due to the favoured stoichiometry. By integrating the developed TOPCon contact over the entire back surface into a bi-facially contacted n-type solar cell with an optimized, diffused front-surface boron emitter, we were able to achieve a new efficiency value record of 24.4 % for this type of cell. This impressively demonstrated the potential of the TOPCon concept.

The project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

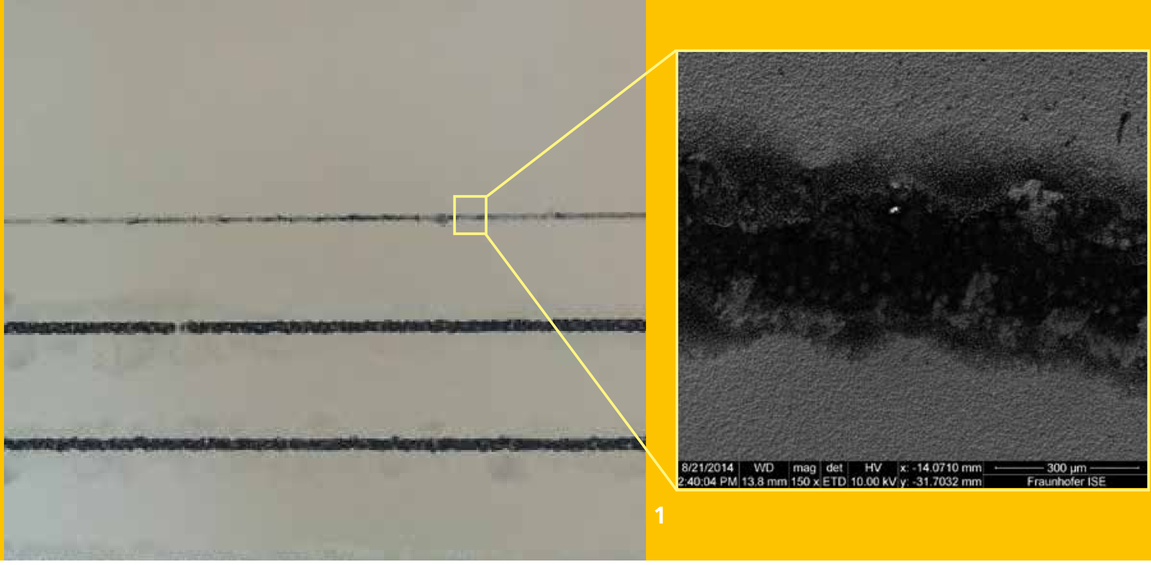
1 *Schematic band diagram for the TOPCon structure.*

2 *Transmission electron micrograph of the TOPCon structure (Transmission electron micrograph prepared at the Gemeinschaftszentrum für Elektronenmikroskopie (GFE) in Jülich).*

3 *Silicon wafer with seven 2 cm x 2 cm solar cells, which have a maximum efficiency value of 24.4 %.*



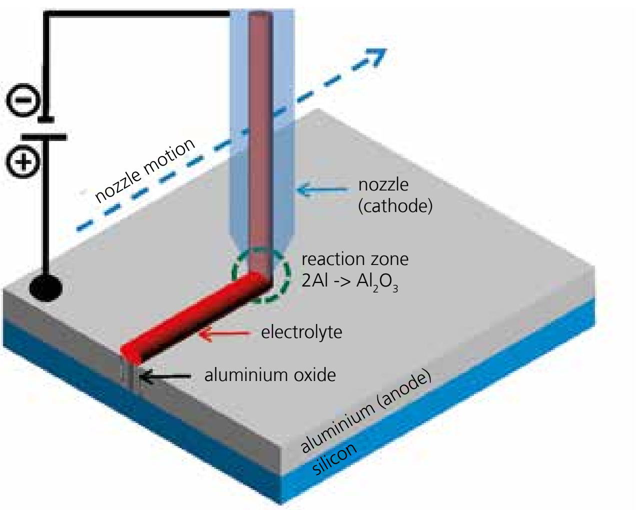
4 *Implied open-circuit voltage of the passivated contact on textured surfaces versus the oxide preparation route for different annealing temperatures.*



ELECTROCHEMICAL STRUCTURING PROCESSES FOR SOLAR CELLS

The most recent generation of silicon solar cells, which has a high efficiency potential, often requires two-dimensional structures which must be produced as cost-effectively as possible. Our goal is to replace the already established but complex processes by rapid electrochemical processes. Electrochemistry offers not only the option of reduction, e. g. for metal deposition, but also the possibility to oxidize materials and thus to dissolve / remove and transform them. Thin films, e. g. aluminium, can be structured quickly and effectively in a single step by such an oxidative process. This reduces costs and opens new perspectives for advanced cell concepts.

Jonas Bartsch, Florian Clement, Raphael Efinger, Markus Glatthaar, **Mathias Kamp**, Axel Maywald, Stefan Glunz

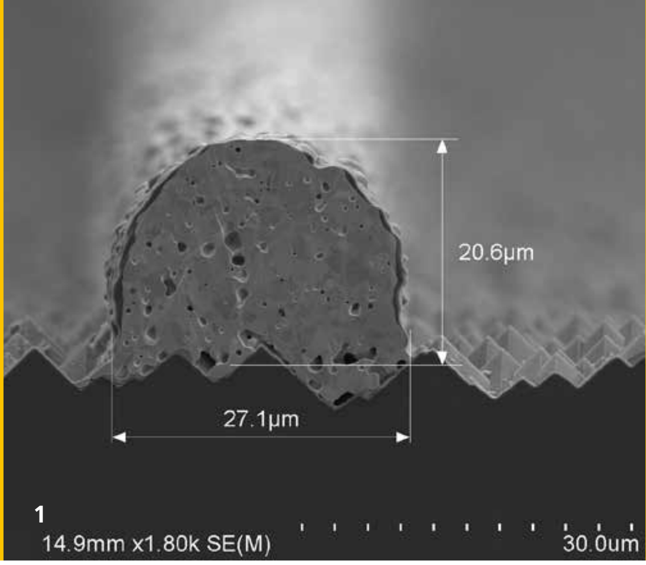


2 *Schematic diagram illustrating the principle of electrochemical structuring of aluminium by electrochemical dispensing.*

1 *Processing result for different feed rates and a scanning electron micrograph of an electrochemically oxidized region.*

Among Si solar cells, back-contact solar cells hold the record for the maximum efficiency value. However, industrial implementation is hindered by the complex, cost-intensive metal structuring processes used to date. The ideal contact material for back-contact solar cells is evaporated aluminium. Electrochemical processes allow Al surfaces which cover the entire back surface to be processed locally and thus enable the metal contacts to be separated.

At Fraunhofer ISE, we have developed and patented various electrochemical processes which can replace expensive masking and etching processes. These include diverse printing processes, in which the printing tool functions as the cathode and either is appropriately structured (screen printing, gravure printing) or creates the desired structure by scanning (dispensing, Fig. 2). The electrolyte is applied to the substrate by the electrically contacted printing tool. This closes the electric circuit and the oxidation process occurs in the desired locations. Depending on the choice of processing parameters, it is possible to produce an electrically insulating aluminium oxide layer or to remove the aluminium completely in order to separate contacts. The entire process lasts only a few seconds. Inexpensive, non-toxic standard chemicals are used, such that the process is attractive for industrial implementation. The process runs at low temperatures and stops automatically at the Si substrate when the structuring is finished. After the Al layer has been structured, it can be electrochemically plated in a self-regulating process and thickened to improve the lateral conductivity.



FINE-LINE METALLIZATION WITH NEW MULTINOZZLE DISPENSER

Contact-free application of extremely fine and homogeneous contact fingers (Fig. 1) by fine-line dispensing allows a front contact grid for a solar cell to be created in a single metallization step. Compared to the result of conventional printing processes, shading losses due to the grid are reduced significantly, without limiting the conductivity of the contact grid. To prepare this process for industrial application, a dispensing robot was developed within the "Gecko" project. The central component is a multinozzle dispensing head which was designed and constructed at Fraunhofer ISE (Fig. 2).

Daniel Biro, Florian Clement, Harald Gentischer, Markus Klawitter, Martin Kuchler, Felix Lorenz, Angel Padilla, **Max Pospischil**, Achim Rastelli, Carlos Rodriguez, Ralf Preu

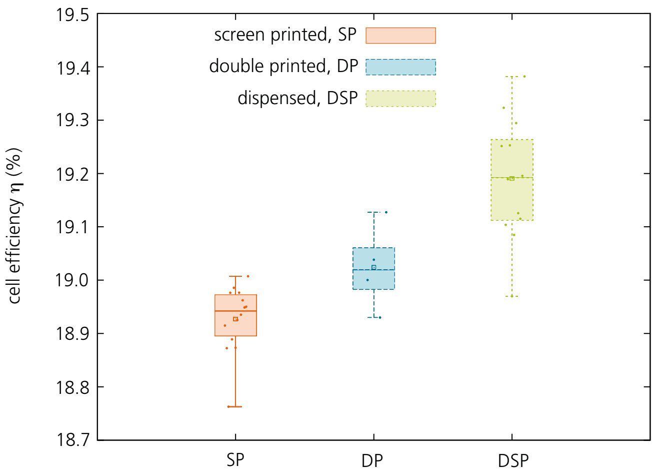
After the dispensing procedure for fine-line metallization of front contacts on crystalline silicon solar cells had been successfully evaluated, with cell efficiency values of up to 20.6 % on MWT-PERC structures, this novel metallization technology was developed to industrial maturity. The intended production throughput required the development of a parallel dispensing print head, which can apply all contact fingers in a single step and simultaneously runs as an extremely stable process.

Initially, all of the highly filled metal pastes to be applied were subject to extensive rheological characterization. On this basis, a simulation model was implemented with which the flow conditions in the print head and nozzles could be accurately investigated, accelerating the development and construction of functional print head prototypes. The result is a print head with a central feed and initially ten parallel nozzles, which can be scaled up as required. It was fabricated by the mechanical workshop of Fraunhofer ISE, meeting the highest demands on precision. Equipped with complex valve technology and sensors, this print head was integrated into a dispensing platform which was developed especially for this application and is suitable for in-line production. Since completion, it has been used successfully to metallize industrial solar cells (Fig. 3).

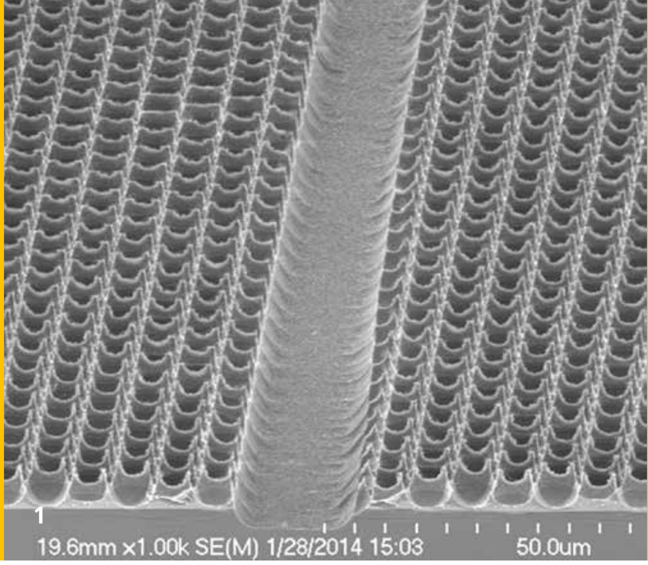
The "Gecko" project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and an industrial consortium consisting of the HERAEUS, MERCK and ASYS companies.

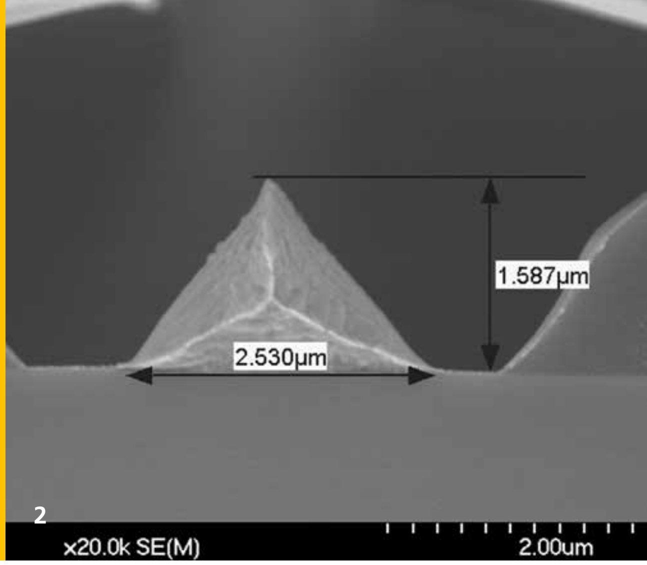
1 *Scanning electron micrograph of a dispensed contact finger on a crystalline solar cell. The large aspect ratio of the contact finger cross-section is clearly visible. This enables high conductivity to be combined with minimal shading.*

2 *Newly developed dispensing robot at Fraunhofer ISE, equipped with a multinozzle print head that was designed and fabricated at the Institute.*



3 *Efficiency values of p-type Cz-Si solar cells with standard aluminium back surfaces. Different metallization processes for the front metal contacts are compared with each other.*

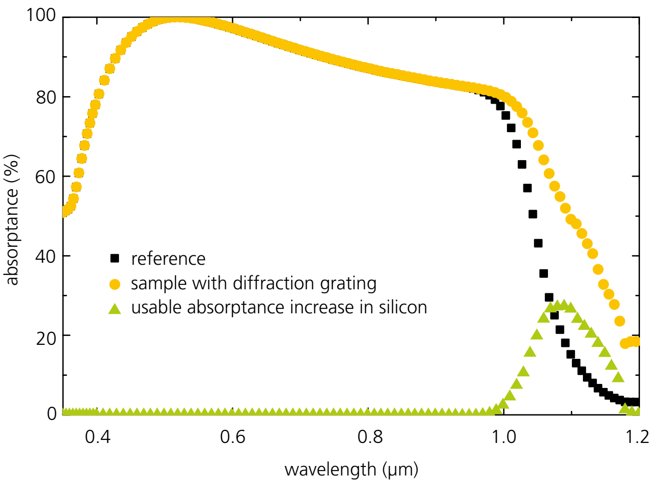




NANOIMPRINT LITHOGRAPHY FOR EXTREMELY FINE SOLAR CELL STRUCTURES

The miniaturization of components is important for photovoltaics. We are investigating nanoimprint lithographic (NIL) processes in order to produce e. g. extremely fine structures for photonic textures or very narrow contact fingers with well-defined morphology. To this purpose, we are using a new high-end facility, which is integrated into a mask aligner for classic photolithography. There, we are able to develop new processes under very well defined conditions, which we then transfer to specifically developed roller NIL equipment.

Simon Barke, Jan Benick, Benedikt Bläsi, Johannes Eisenlohr, Jan Christoph Goldschmidt, **Hubert Hauser**, Claas Müller*, Patrick Schneider, Sonja Seitz, Katharina Tokai, Nico Tucher, Christine Wellens, Werner Platzer (* IMTEK, Albert Ludwig University, Freiburg)



3 *Absorptance measurements of 200 µm thick solar cell precursors (with ARC and back-surface metallization), in which the effect of back-surface diffraction gratings in the long-wavelength spectral range was investigated. The green spectrum shows the increase in absorptance in silicon as determined by wave-optical simulation.*

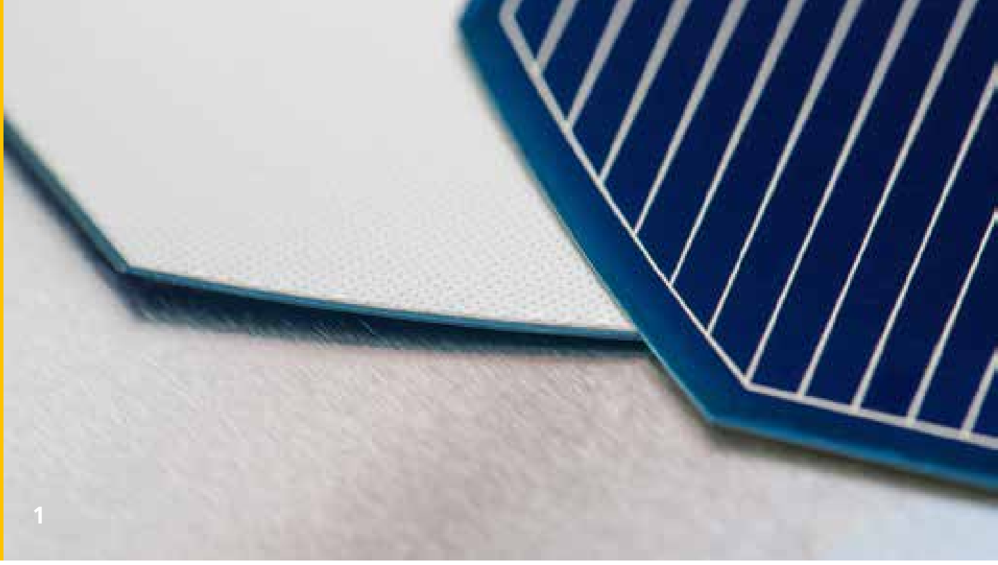
1 *Scanning electron micrograph of a structure that was transferred to silicon. The etching mask used was transferred in a single processing step by NIL. The hexagonal structure (honeycomb texture) has an integrated groove for later metallization.*

2 *Fine-line metal contact with a prismatic profile, to effectively minimize shading by reflection effects.*

Although the structural resolution required in photovoltaics is clearly coarser than in microelectronics, new features applying NIL processes are also conceivable there. They combine the properties of extremely fine structural resolution, which are otherwise possible only with complicated electron-beam scribing, with large-area replication with very high throughput such as roll-to-roll processes. Integration of the new NIL tool from the EVG company into a mask aligner meant that very diverse, finely resolved structures, which previously had been possible only on small areas in the laboratory, could be integrated into products. To produce the master structures, we use a combination of various lithographic processes such as interference lithography, NIL, hot embossing and photolithography, as well as anisotropic etching processes. Embossing stamps can then be replicated from the master structures, so that many different characteristics can be reproduced in a single NIL step.

In the Fraunhofer "PV-NIL" project, we are investigating etching masks which unite the morphology for an efficient texture and the finest contact fingers. We are also investigating the production of finest contact fingers with a prismatic cross-section, in order to minimize the effective shading.

In the "Fortes" project, which is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), we use fine structural resolution to create diffraction gratings in solar cells. The new NIL equipment was financed with strategic investment funds from the Fraunhofer-Gesellschaft.



HIGH-EFFICIENCY INDUSTRIAL SOLAR CELLS WITH FOIL METALLIZATION

Solar cells with passivated rear contacts (PERC) allow higher efficiency values to be attained than conventional cells. This technology is thus being tested in pilot production lines and has already been transferred to mass production in a few cases. However, additional processing steps make it more complex and expensive, so that the cost advantage is slight, despite the higher efficiency. A technique, which has been developed at Fraunhofer ISE to laser-weld conventional aluminium foil to the silicon wafer, simplifies the production of PERC cells significantly, offers the potential for higher efficiency values and simultaneously is significantly less expensive.

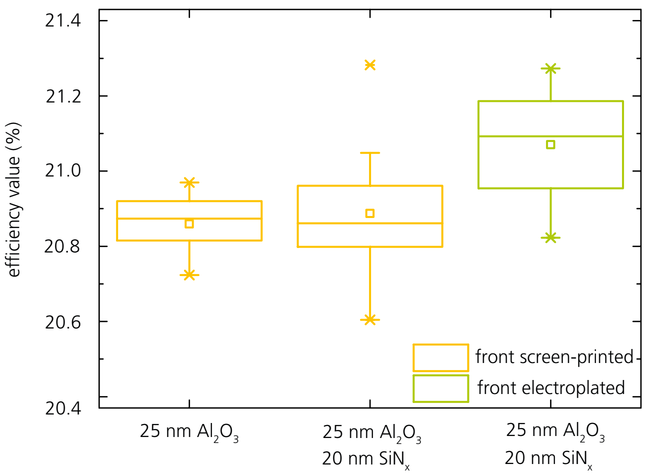
Andreas Brand, Martin Graf, **Jan Nekarda**, Ralf Preu

The aluminium foil is alloyed through the passivation layer and welded with the silicon by individual laser pulses. These contact points represent the mechanical and electrical connection between the foil electrode and the silicon wafer. The procedure results in a short circuit current which is up to 0.3 mA/cm² higher due to improved optical properties. At the same time, the passivation layer thickness is reduced by 75 %. In comparison to the routinely used electrode consisting of printed and fired metallic paste, the "cold" foil metallization affects the quality of the passivation layer less. This simplifies the transfer of PERC technology into existing production lines and enables higher open-circuit voltages. In addition, foil metallization offers a substantial cost advantage, as the material costs for the electrodes and the production costs of passivation are reduced, and at least two production steps can be eliminated.

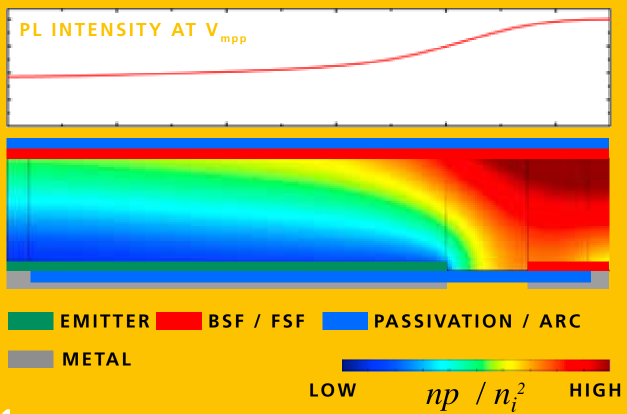
Recently, compatibility with a galvanically deposited front contact grid was demonstrated, which enables better light trapping and does not require any silver. Also, the feasibility of connecting this type of solar cell with conventional connection technology was demonstrated using an inexpensive roll-to-roll coating process.

In the currently running "FolMet" project, which is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), these approaches have already led to the production of industrially relevant solar cells without silver, with a thinner back-surface passivation layer and efficiency values exceeding 21 %.

1 *Front and back of a 156 x 156 mm² industrial solar cell with a back-surface passivation layer and laser-welded contacts of conventional aluminium foil.*



2 *Efficiency values of industrial PERC solar cells without busbars, with back-surface foil metallization, without or with a thinner SiN_x protective layer on the back surface, and printed / fired (yellow) or galvanically plated (green) front metallization.*



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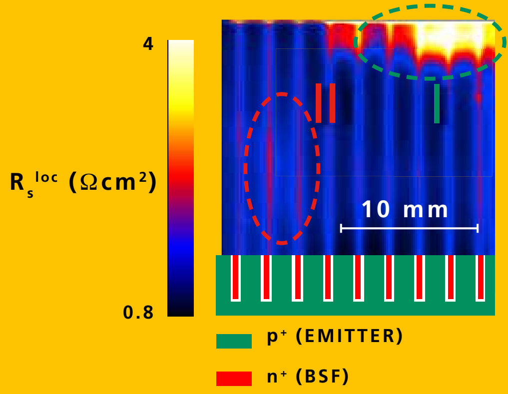
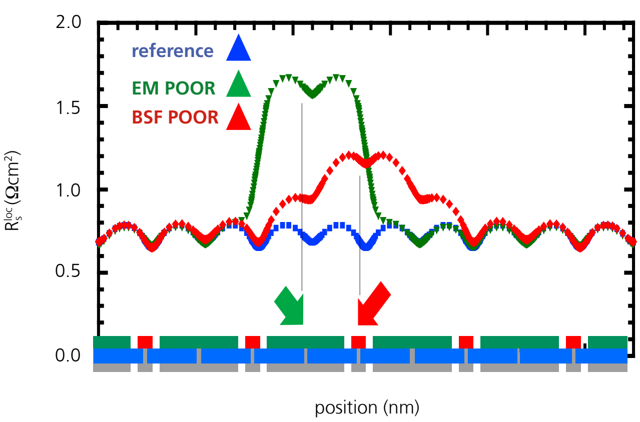


2

PHOTOLUMINESCENCE-BASED CHARACTERIZATION OF REAR-CONTACT CELLS

Rear-contact cells achieve highest efficiency values but typically feature complex contact and doping structures. This means that lateral effects play a significant role for charge transport. Existing spatially resolved analytical methods could not describe this adequately. By combining simulation and imaging luminescence measurements, Fraunhofer ISE has now created a quantitative method to analyze important, laterally strongly varying cell properties. Thus, charge carrier recombination at all interfaces and local series resistances can now be detected and causes for performance loss in solar cells identified.

Nikolaus Hagedorn, Roman Keding, Sven Kluska, **Milan Padilla**, Christian Reichel, Martin Schubert, Wilhelm Warta, Stefan Glunz

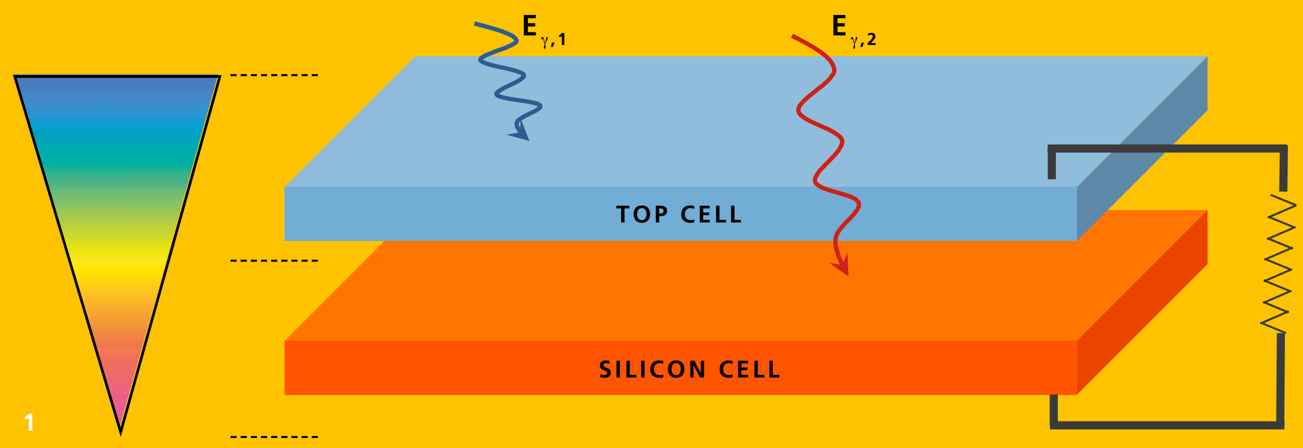


3 *Simulation of the local series resistance in the case of a single poor emitter (EM) or base (BSF) in cross-section.*

1 *Modelled intensity profile for a photoluminescence measurement under V_{oc} conditions (above), based on charge carrier density simulation (below), which takes the differing surface recombination rates at the front, the contact zones and regions between contacts into account.*

2 *Top view of the photoluminescence-based series resistance measurement of the front of a cell, which shows higher contact resistance at both the emitter contact (green) and the base contact (red).*

The highest cell efficiency values can be achieved with rear-contact cells with complex cell architecture. This structure makes it difficult to characterize various cell parameters with accurate spatial resolution. Significant lateral current flows, which depend particularly on the type of charge carrier, have a large effect on camera-based luminescence measurements and thus place high demands on the evaluation of these measurements. Our new approach combines multi-dimensional cell modelling with experimental photoluminescence analysis. Modelling the local charge carrier densities allows the simulation of intensity profiles that can be expected in the photoluminescence measurement (Fig. 1), so that information can be gained on the differing surface recombination rates on the front of the cell and the base and emitter contacts on the back of the cell. By varying the modelled cell parameters, the result can be adapted to the measurement, allowing the occurring recombination rates to be determined. Local series resistance problems can be identified analogously on IBC solar cells and determined quantitatively (Fig. 2 and 3). Modelling the lateral current flows from both types of charge carriers allows the local series resistance, which results from locally confined poor emitter and base contacts, to be quantified. With our new evaluation approach, it is now possible to identify and quantify local recombination and contact problems, supporting targeted cell optimization.



EFFICIENCY VALUES EXCEEDING 30 % WITH SILICON-BASED TANDEM SOLAR CELLS

Tandem solar cells consist of stacks of several solar cells of different materials. If these solar cells have different band gaps, almost every part of the solar spectrum can be ideally used. Very high efficiency values can be obtained as a result. In order to take advantage of the developmental lead which silicon solar cells command, the technologically most attractive approach to achieve efficiency values exceeding 30 % is to deposit either III-V semiconductor or novel perovskite solar cells onto a silicon solar cell to create a tandem cell. An important field of research here is the interface between the top cell and the silicon solar cell.

1 Schematic representation of the tandem cell concept with a silicon solar cell as the bottom cell. The two sub-cells absorb in different spectral ranges and can thus convert the photon energy ideally into electricity. This makes theoretical efficiency values > 40 % possible. Either III-V semiconductors or perovskite solar cells can be used for the top cells, which are positioned on top of the silicon solar cell.

Jan Benick, Frank Dimroth, Stefanie Essig, Jan Christoph Goldschmidt, **Martin Hermle**, Andreas Hinsch, Stefan Janz, David Lackner, Welmoed Veurman, Stefan Glunz

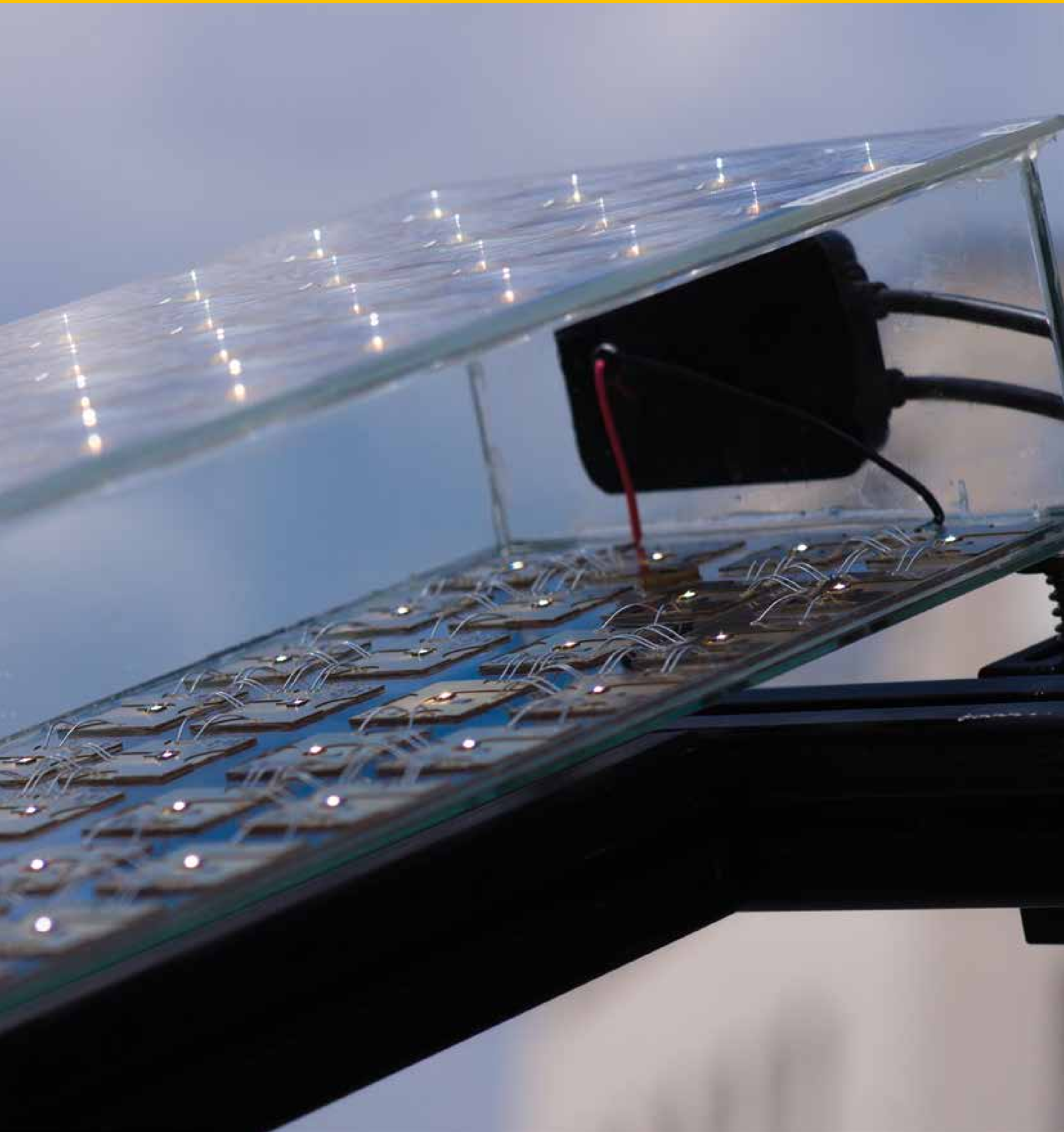
Silicon solar cells command a market share of about 90 % and have reached a high level of technological maturity. One possibility to raise the efficiency value above the theoretical limit of 29.4 % for silicon solar cells is offered by tandem solar cells, which consist of several solar cells stacked on top of each other (Fig. 1). By using silicon for the lowest solar cell, efficiency values exceeding 30 % are possible and the technology can benefit from the advanced development stage of commercially dominant silicon technology.

At Fraunhofer ISE, tandem cells have already been successfully produced which consist of a silicon bottom cell and a GaInP/GaAs top solar cell. The Si cell and the III-V solar cell were produced separately and then connected electrically and mechanically with each other via a semiconductor bond. With this approach, already an efficiency value of 25.6 % (V_{oc} = 2.89 V) was achieved in initial experiments with an illumination intensity of one sun. Other methods to connect the sub-cells are being evaluated in addition to semiconductor bonding. As an alternative to solar cells of III-V semiconductors, perovskite solar cells are also being investigated at present as candidates for the top cells. Perovskite solar cells can be produced very cost-effectively and their efficiency value has been increased within only a few years to more than 19 %. Furthermore, their band gap is ideal for combination with a silicon solar cell in a tandem solar cell.

For all tandem applications with silicon as the bottom cell and a series interconnection, optimal absorption in the sub-cells is very important. As the photocurrent must be equal in all sub-cells for a series connection, it is necessary to optimize the absorption of solar radiation. As the front of the silicon solar cell is not allowed to have any texture in some concepts, we at Fraunhofer ISE are developing optimized, light-diffracting structures at the back of the solar cell, which significantly lengthen the light path within the silicon and thus enable maximum absorption in the silicon.

The goal of all these developments is to implement solar cells with efficiency values exceeding 30 % and modules with efficiency values higher than 28 %, so that a new generation of silicon-based solar cells can be developed and the levellized cost of photovoltaic electricity can be further reduced.

III-V AND CONCENTRATOR PHOTOVOLTAICS



The activities of Fraunhofer ISE in this field address the requirements resulting from the market for space and terrestrial photovoltaics. Satellites in space are equipped exclusively with highly efficient III-V multi-junction solar cells. Responding to the special conditions in space – such as the bombardment of material by high-energy electrons and protons and the expense of launching satellites into space – we are developing new solar cell architectures, which achieve yet higher efficiency values for even less weight. Also for terrestrial, concentrating photovoltaic systems, research approaches are determined by the goals of high efficiency and reduced costs for production processes. The market share of concentrator photovoltaics is still low, with about 100 MW/year. We support our clients in further developing the technology and the market. To this end, we also work actively in the IEC standardization committees.

In order to achieve higher efficiency and lower costs, we optimize processing technology, develop materials and new manufacturing technology. For example, we are investigating materials systems of GaInNAs and ternary and quaternary III-V semiconductors containing aluminium for use in monolithically grown quintuple-junction and sextuple-junction solar cells. For metamorphic growth concepts, where materials with different lattice constants are grown, we design suitable buffer structures, on which we can implement high-quality solar cell structures. One example for the application of such structures is the growth of multi-junction solar cells on silicon. In the long term, such multi-junction solar cells on Si are also interesting for use in flat-plate modules.

The wafer-bonding process is another important technological topic. It allows semiconductor layers to be bonded with each other, so that we can combine different semiconductors such as GaSb, GaAs, InP, Si or Ge. This year, we were able to increase the efficiency value again and achieved a new record value of 46.0 % with a wafer-bonded quadruple-junction solar cell. The record cell was developed together with our partners, Soitec Solar and CEA-Leti.

A special application of III-V photovoltaic cells is their use under monochromatic irradiation from LEDs or lasers. Very high conversion efficiency can be achieved here, so that this type of cell is used in wireless power supply systems.

In order to use III-V multi-junction solar cells in terrestrial applications, we develop highly concentrating PV systems. To this end, we investigate and test optical components which concentrate sunlight by factors of 300 to 1000, before it is converted to electricity in the III-V multi-junction solar cell. We are working on very diverse module concepts, to achieve higher efficiency values and lower production costs. Thus, we were able to achieve a new world record efficiency value of 36.7 % under concentrator standard test conditions (CSTC) with our FLATCON© module. Quadruple-junction solar cells were used in this module for the first time.

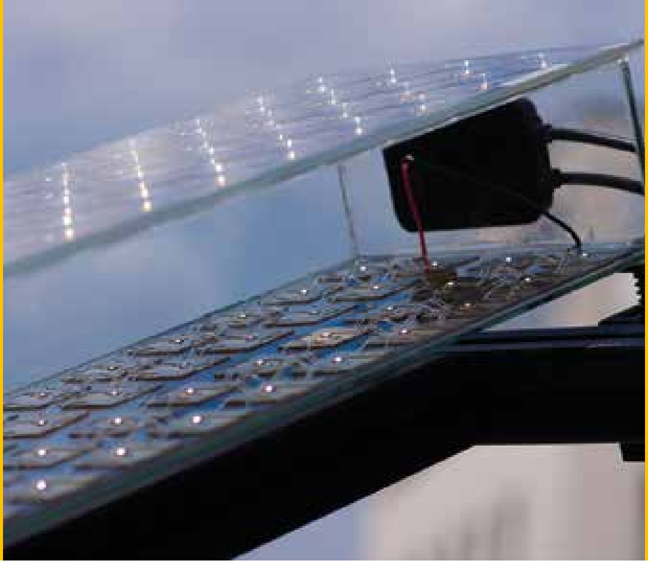
In our ConTEC (Concentrator Technology and Evaluation Centre), we investigate module production processes and reliability, and prepare quality assurance concepts. Clients use our expertise in thermal, optical and electrical simulation and characterization. We optimize and develop processes and innovative systems.

Furthermore, we also work on low-concentration systems. These cover the concentration range from a factor of 2 to 30. We cooperate with our clients in developing optical concentrators, mounting solar cells and receivers, and designing and measuring systems. In our PV-TEC (Photovoltaic Technology Evaluation Centre), series of special Si solar cells can be produced for specific applications of our clients.

FURTHER INFORMATION

Staff	73
Full-time equivalent staff	56
Journal articles and contributions to books	21
Lectures and conference papers	49
Newly granted patents	5

www.ise.fraunhofer.de/en/publications/20



FLATCON© concentrator module with an efficiency value of 36.7 %.

CONTACTS

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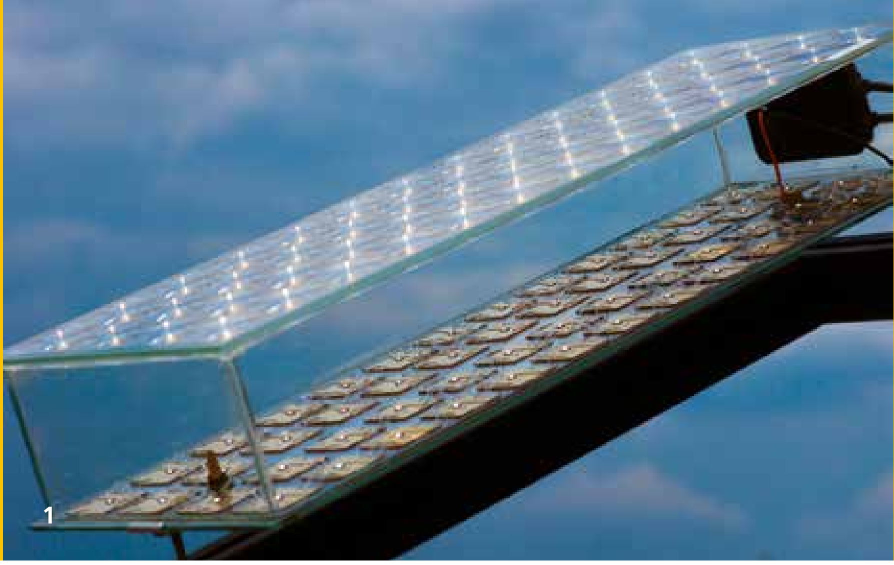


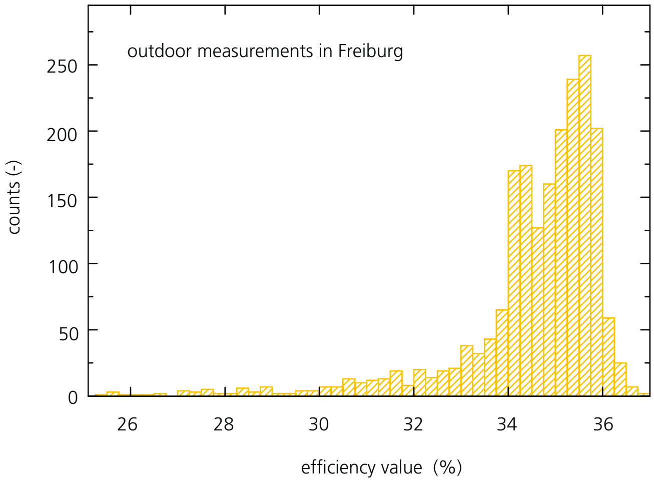
FLATCON® MODULE WITH QUADRUPLE-JUNCTION SOLAR CELLS AND 36.7 % EFFICIENCY

An advantage of concentrator photovoltaics (CPV) is its potential for extremely high efficiency values. The basis for this is provided by multi-junction solar cells. Today, triple-junction solar cells are used in commercial CPV systems. More recent solar cell concepts based on quadruple-junction cells, such as we are developing at Fraunhofer ISE, already achieve significantly higher efficiency values. Now we have successfully integrated quadruple-junction solar cells into the Fraunhofer ISE FLATCON© module for the first time. Thereby, we achieved the internationally unequalled efficiency value for solar modules of 36.7 %.

Armin Bösch, Alexander Dilger, Frank Dimroth, Tobias Dörsam, Thorsten Hornung, Gerald Siefer, **Marc Steiner**, Maike Wiesenfarth, Andreas Bett

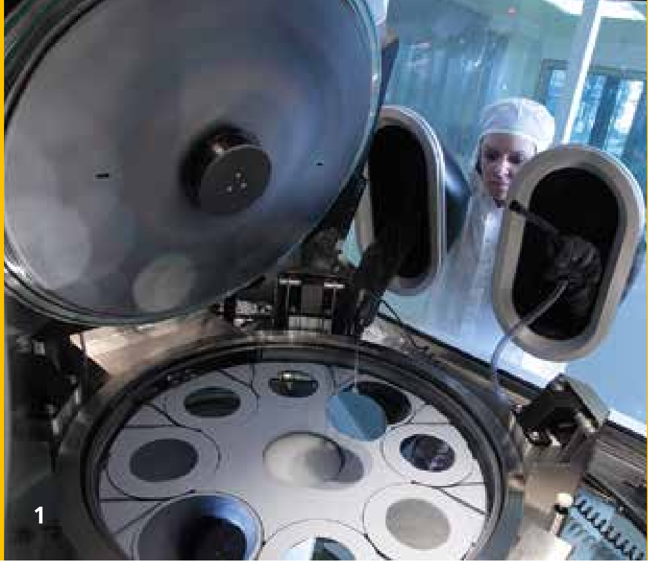
The FLATCON© concentrator modules that we developed contain Fresnel lenses to concentrate the sunlight several hundred times onto tiny (millimetre scale) but highly efficient solar cells. In this way, solar cell material can be saved. The application of extremely high-performance multi-junction solar cells thus becomes feasible. Multi-junction solar cells consist of any number of specialized sub-cells which are stacked on top of each other. The larger the number of sub-cells, the more efficient is the conversion of sunlight to electricity. In commercial CPV systems, triple-junction solar cells are currently being used, as these are industrially available. We have cooperated with our partners, Soitec Solar and CEA-Leti, to produce quadruple-junction solar cells, which achieve an efficiency value of up to 46 %. Usage of such quadruple-junction solar cells in a concentrator module can substantially increase the electricity yield. We have integrated quadruple-junction solar cells into our FLATCON© CPV modules for the first time (Fig. 1). These modules were electrically characterized on our outdoor test stand – and thus under application conditions. In Fig. 2, the efficiency values which were measured there in the period from April to May 2014 are presented as a histogram. On the basis of this characterization, the module efficiency value under Concentrator Standard Test Conditions (CSTC: 1000 W/m² solar irradiance, 25 °C cell temperature) was determined to be 36.7 %.

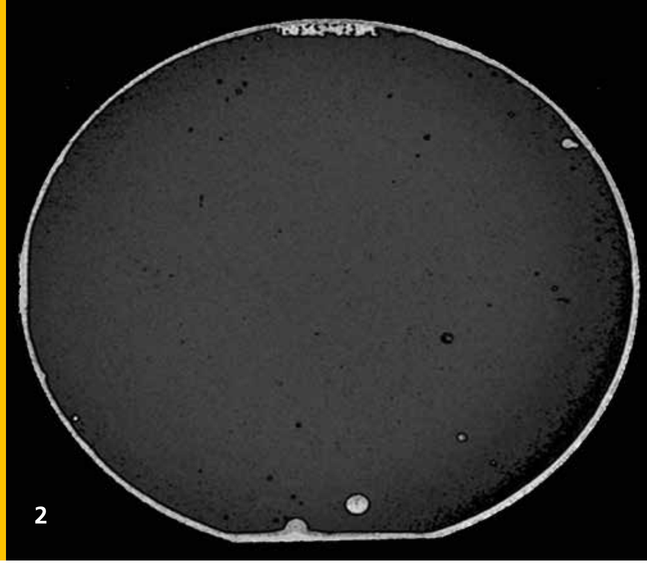
1 *FLATCON© (Fresnel Lens All-Glass Tandem Cell Concentrator) module consisting of 52 pairs of solar cells and Fresnel lenses. The module was produced at Fraunhofer ISE. The alignment of the cells with respect to the lens is decisive and is achieved with the help of special mounting guides. It must ensure that each of the 52 lenses concentrates the sunlight directly onto the centre of the respective solar cell.*



2 *Distribution of the electrical efficiency values of a FLATCON© concentrator photovoltaic module equipped with quadruple-junction solar cells, measured under the prevailing meteorological conditions at Fraunhofer ISE in Freiburg. The median of the distribution is 34.9 %. The efficiency value at concentrator standard conditions derived from this distribution is 36.7 %.*

The project was partly supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

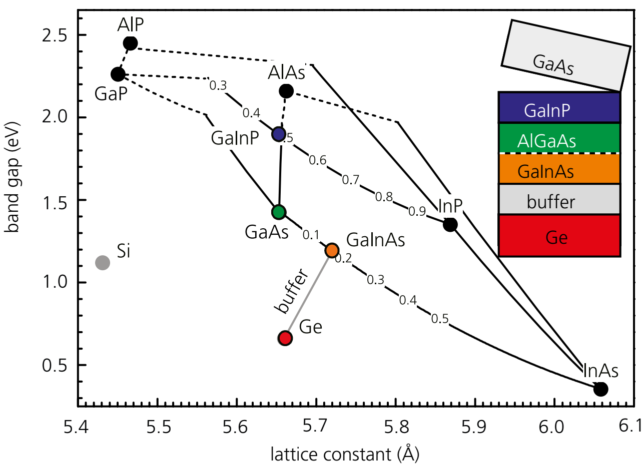




HIGHLY EFFICIENT, BONDED QUADRUPLE-JUNCTION SOLAR CELLS ON GERMANIUM

Higher cell efficiency values reduce the total costs of PV systems. Among III-V semiconductor solar cells, new promising cell concepts have made an efficiency value of 50 % appear feasible. To achieve this, solar cells with at least four photoactive sub-cells are needed. We are developing a cost-effective concept based on the III-V compound semiconductors, GaInP, AlGaAs, GaInAs, and Ge. Two tandem cells are directly wafer-bonded by being pressed onto each other with great force (10 kN). This occurs without any adhesive or other intermediate layers. The resulting connection is mechanically stable and has a low electric resistance (Fig. 2).

Frank Dimroth, David Lackner, **Markus Niemeyer**, Jens Ohlmann, Axel Panamatschuk, Sophie Stättner, Thomas Tibbits, Katrin Wagner, Alexander Wekkeli, Andreas Bett



3 *Band gaps versus lattice constants of some III-V compound semiconductors, and Ge and Si. The sub-cells used in the presented concept are indicated and the schematic diagram shows the quadruple-junction cell with its photo-inactive buffer and the wafer bond indicated by the white dashed line.*

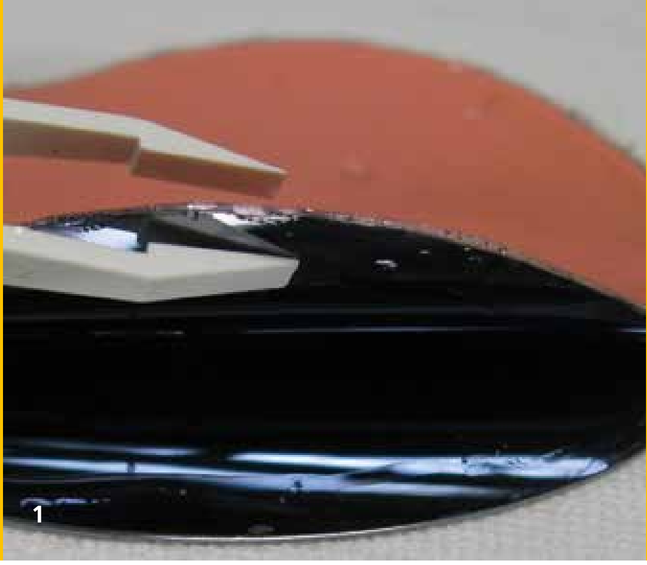
1 *Industrial reactor to deposit III-V semiconductor films. Up to eight 6" substrates can be coated simultaneously.*

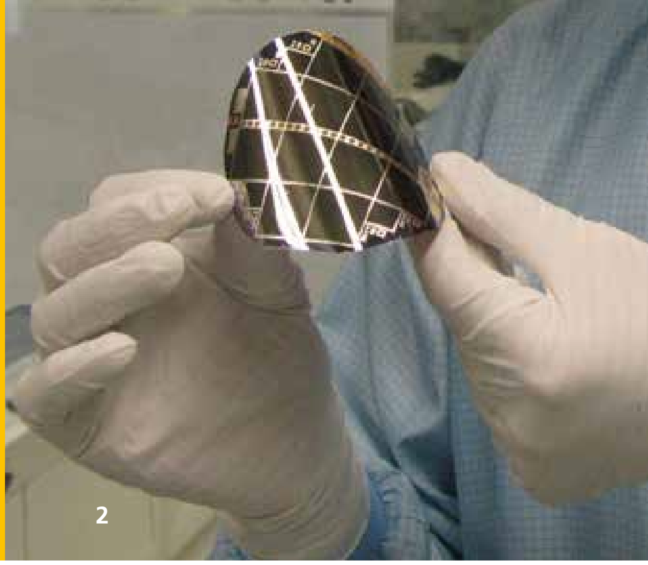
2 *Ultrasonic image of a 4" wafer bond between a top GaInP/GaAs and a bottom GaInAs/Ge tandem solar cell. Unbonded areas appear white.*

The efficiency value of solar cells with a single pn junction is theoretically limited to a value of only about 30 %. This value can be increased by adding further pn junctions. With the right choice of band gaps, an efficiency value exceeding 50 % can be achieved practically with four pn junctions under concentrated light. The highest efficiency values are achieved with material combinations of III-V compound semiconductors such as GaAs or GaInP.

In metal-organic vapour phase epitaxy (MOVPE, Fig. 1), crystalline III-V semiconductor structures are deposited onto substrates. The highest quality is achieved by depositing materials with the same lattice constants. However, this greatly restricts the possible band gaps available. In order to combine materials with differing lattice constants, we use two methods. In the first, cell structures are deposited onto two substrates with different lattice constants and connected by wafer bonding. In the second, the lattice constant is slowly changed within a buffer layer, which itself is not photoactive, on one of the two substrates. Resulting crystal defects can be restricted to this part of the structure by clever buffer design. In these ways, it becomes feasible to combine sub-cells with band gaps which are close to the optimal selection. This type of quadruple-junction cell has already achieved an efficiency value of 34.5 % (AM 1.5d, 1 sun). In the future, these solar cells will be further developed for applications with concentrated light and promise then to deliver highest efficiency values of up to 50 %.

The project is supported by the European Commission within the "NGCPV" project.





EXTREMELY THIN CELLS ON METAL FOIL WITH RECYCLABLE SUBSTRATES

Costs for highly efficient III-V multi-junction solar cells can be reduced if the valuable GaAs substrates are recycled and used again for the growth of further solar cells. To achieve this, we are developing a process in which an extremely thin solar cell is separated from its substrate by selective etching. The cell is mechanically stabilized by a thin metal foil. These flexible cells can be used cost-effectively e. g. in low-concentrating PV systems. We cooperate in this development work with our research partners from CEA-Leti and INES.

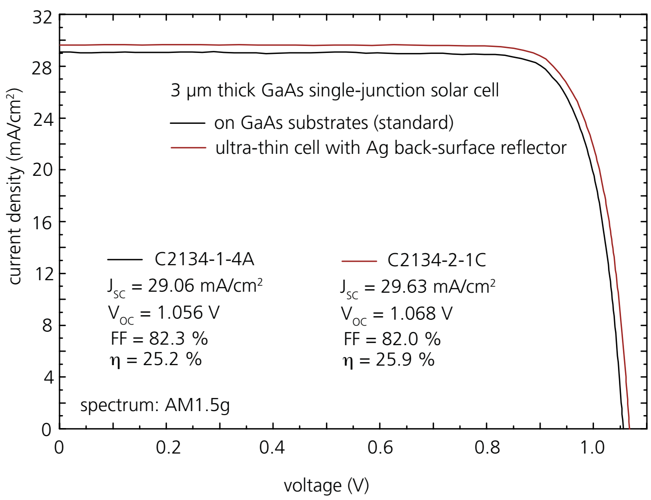
Simon Barke, Sandra Bau, Frank Dimroth, Matthias Grave, **Vera Klinger**, Daniel Neves Micha, Eduard Oliva, Manuela Scheer, Tom Tibbits, Katrin Wagner, Andreas Bett

Multi-junction solar cells achieve the highest efficiency values for the conversion of sunlight into electricity, currently with values of up to 46.0 %. The III-V semiconductor substrates, which are used as the base for epitaxial growth, represent a significant cost factor, although they do not contribute to the actual function of the solar cell. Thus, it is economically advantageous to separate the solar cell, which is only a few micrometres thick, from the substrate and then to reuse the substrate.

We have developed a procedure to do this, in which a so-called sacrificial layer is grown between the solar cell and the substrate, and then selectively etched in a wet-chemical process. The extremely thin solar cell and the substrate are separated in this way. Beforehand, thin metal foil is attached to mechanically stabilize the solar cell. After the substrate has been removed, a flexible and very light solar cell results. In addition, the metal foil helps to separate the solar cell and the substrate, as it causes the solar cell to roll up slightly. The etching process can thus occur without any mechanical agents. The initial substrate can be used again subsequently as the base for further solar cell growth, without any further, expensive preparation process.

1 Separation of the extremely thin solar cell on metal foil from the substrate for epitaxial growth by wet-chemical selective etching.

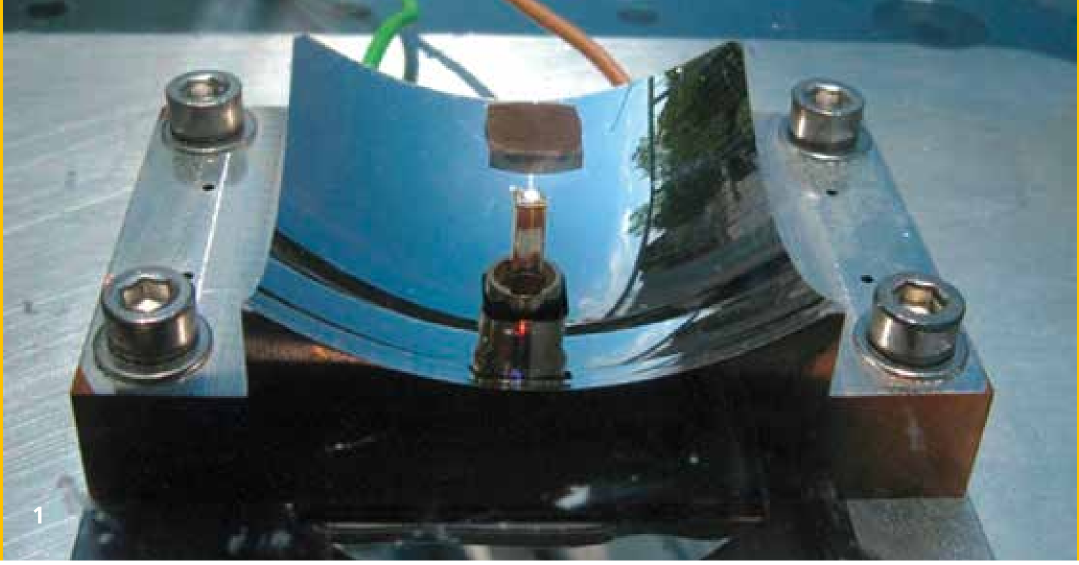
2 Extremely thin, multi-junction solar cells, processed on thin, flexible metal foil.



3 Current-voltage characteristic of an extremely thin, single-junction GaAs cell on metal foil with a back-surface reflector and an efficiency value of 25.9 %.

Applying this process, GaAs single-junction solar cells were produced with an efficiency value of 25.9 % under an AM 1.5g spectrum. These solar cells and tandem solar cells can be used cost-effectively e. g. in low-concentrating photovoltaic systems.

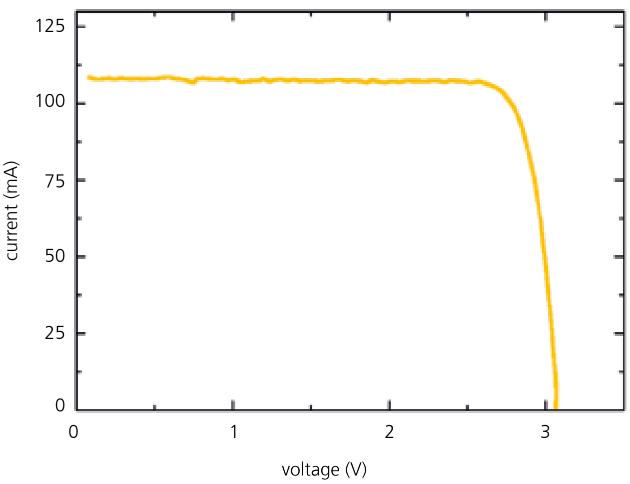
The work has been carried out within the "VirtualLab" project, in which we cooperate with our partners at CEA-Leti and INES.



CPV MODULE TECHNOLOGY BASED ON CASSEGRAIN OPTICS

In concentrator photovoltaics, sunlight is focussed by a cost-effective optical system onto a small solar cell. Curved reflectors can be used to this purpose, e. g. in the Cassegrain configuration. In it, the light from a concave mirror (primary optics) is directed onto the solar cell by a smaller, convex mirror (secondary optics). This results in module configurations with minimal height. We have developed and evaluated a prototype module based on this concept. We achieved a very good optical efficiency of 80 % for a geometrical concentration factor of 1000x. By choosing an elevated position for the solar cell, we eliminate the need for a third optical system, so-called tertiary optics.

Armin Bösch, Max Dreger, Thorsten Hornung, Arne Kisser, Tobias Schmid, **Maike Wiesenfarth**, Andreas Bett

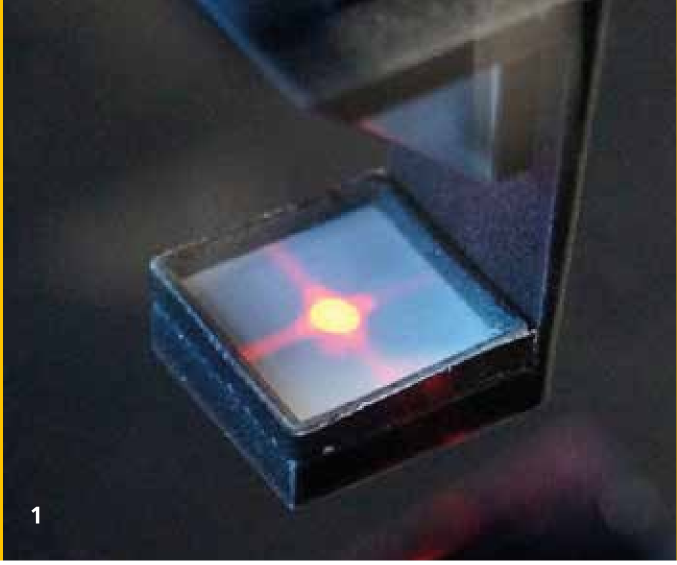


2 *Current-voltage characteristic of our prototype with Cassegrain optics, as determined in an outdoor measurement. The module was measured for several months in an outdoor test stand at Fraunhofer ISE. During the measurement on 01.08.2013 at 08:35, 31.6 % of the incident solar energy was converted to electricity.*

1 *Concentrator PV module unit, consisting of Cassegrain reflector optics with a solar cell. Sunlight is concentrated by a factor of more than 1000 onto the solar cell with an area of 1 mm². The solar cell is located between the primary and the secondary optics.*

In our research on concentrator photovoltaics, we develop and analyze various module concepts. Our most recent development is a module with Cassegrain reflector optics. A major advantage of mirror optics is that chromatic aberration does not occur. In addition, we expect that the temperature dependence will be less pronounced than for Fresnel lenses. The aperture area of the module is relatively small, with an edge length of the primary optics being 32 mm. This means that a module height of less than 25 mm can be achieved. With these small dimensions, it is possible to cool the solar cell passively, i. e. to mount it on a heat spreader and transfer heat to the surroundings by convection and radiation. In addition, we mount the solar cell on a small tower. This means that the solar cell is located between the primary and the secondary optics (Fig. 1). In this way, we achieve a large acceptance angle of 0.75°, such that even if the module were misaligned by 0.75° with respect to the solar radiation, 90 % of the power would still be generated. A major aspect of our project involved constructing and investigating the concentrator optics. The optics was fabricated by diamond machining. In addition we developed optics which was produced by an injection moulding process that would be suitable for mass production. We compared the two types of optics in laboratory and outdoor measurements. The current-voltage characteristic from an outdoor measurement of the concentrator module is shown in Fig. 2. Efficiency values of 31.6 % were achieved. With continuous outdoor measurements, we are now investigating the long-term performance.

The project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).



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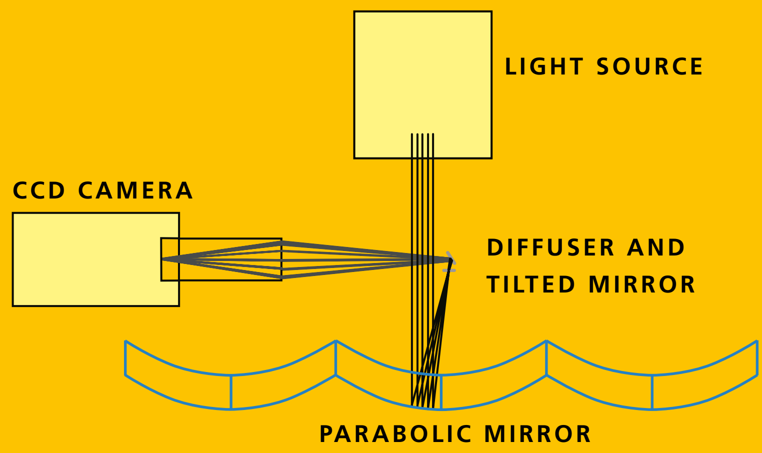


2

CHARACTERIZATION OF PARABOLIC REFLECTORS FOR CONCENTRATOR PV

Concentrator photovoltaics (CPV) uses tiny solar cells for electricity generation and a larger area with optics to collect and focus the sunlight. Parabolic reflectors are suitable optical components, as they do not suffer from chromatic aberration, in contrast to lenses. The distribution of the focussed sunlight over the solar cell is one decisive factor affecting the efficiency of the entire system. We determine this distribution in a newly developed measurement set-up and use it to predict the system performance. With this information, we can optimize the geometrical parameters of the parabolic reflector and its fabrication process, as well as carry out quality control.

Thorsten Hornung, Peter Nitz, **Tobias Schmid**, Werner Platzer

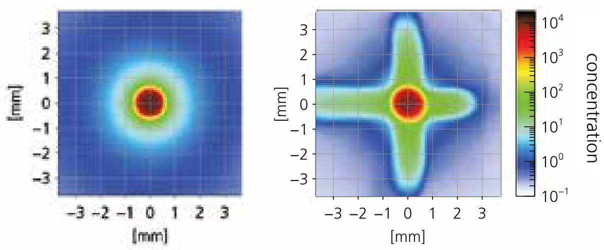
CPV systems concentrate direct sunlight onto small solar cells, e. g. with parabolic reflectors. The optical properties of the reflectors are characterized in our newly developed measurement set-up. The measurement system measures the spatial distribution of the optical concentration over the focal plane of the parabolic reflector, where the solar cell would be located in a concentrator PV system. The measurement thus provides direct information on the spatial distribution of radiation over the cell in the real system.

As the focus of a parabolic reflector is located within its entrance aperture, a detector located there in the measurement system would obstruct the incident radiation. For this reason, we have installed a small diffuser plate there, which is imaged with the help of a light-deflecting mirror by a CCD camera mounted outside the entrance aperture (Fig. 2).

The difference between two parabolic reflectors, which were fabricated by different production processes, becomes clearly visible in the spatial light distributions determined with the measurement set-up. One reflector concentrates the light very well onto a central point (Fig. 3, left). The other reflector leads to a star-like distribution of the light in the focal plane (Fig. 3, right). The measurement results provide information about the influence of surface deviations on the power yield of the CPV system, and lead to valuable conclusions concerning further improvement of the optical concentrator system.

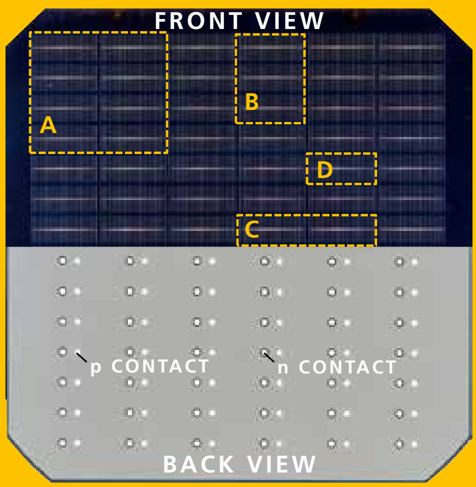
1 *Diffuser plate in the focal plane of a parabolic reflector during a measurement. The star-shaped light distribution (shown in a false-colour representation) allows surface deviations to be identified which affect the power yield of the CPV system. The actual measurement is made by the camera via a light-deflecting mirror, which can be seen from the side as a grey triangle at the top of the photo.*

2 *Schematic configuration of the measurement set-up. A diffuser plate is located in the focal plane of the parabolic mirror, which is photographed via a light-deflecting mirror. The individual mirrors can be positioned beneath the light source with motorized drive units.*



3 *Measured spatial distribution of the radiation concentration in the focal plane of two parabolic reflectors. The reflector which creates the concentration distribution in the left-hand image has a very accurate shape whereas the star-shaped light distribution in the right-hand image results from minimal surface deviations caused by the production process for the reflector investigated there.*

The project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).



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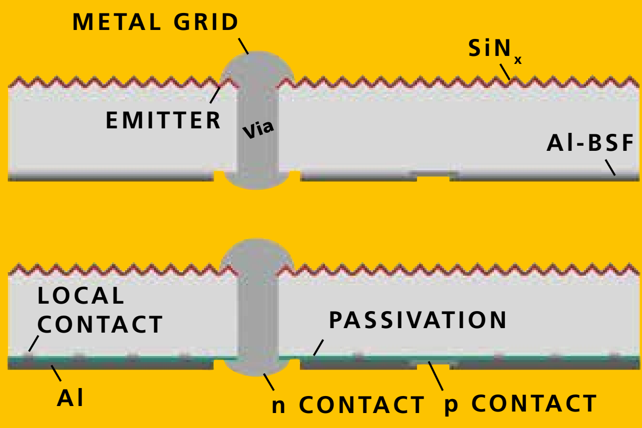
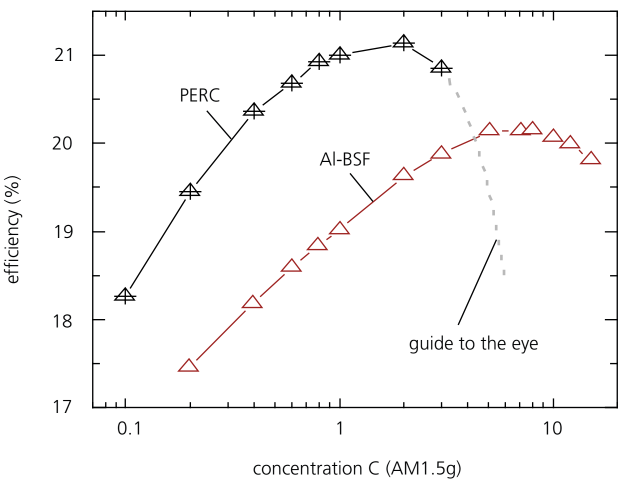


2

ALL-PURPOSE MWT CONCEPT FOR SOLAR CELLS OF VARIABLE DIMENSIONS

In addition to the conventional usage of Si solar cells in flat solar panels, there are applications which are particularly optimized for radiation concentrated by either low or, more commonly, high concentration factors. This application is distinguished by the requirement that the solar cells used must transport either very low or particularly high current densities. In addition, this type of application demands variable dimensions and a flexible current-voltage ratio from the finished product. For this context, we have developed the All-Purpose-Metal-Wrap-Through (AP-MWT) concept. Peak efficiency values of 20.2 % have been achieved for an irradiance level of 1W/cm² (C = 10), 21.0 % at C = 1 and 18.3 % for C = 0.1.

Daniel Biro, Florian Clement, Matthieu Ebert, Ulrich Eitner, **Tobias Fellmeth**, Ingrid Hädrich, Ralf Preu



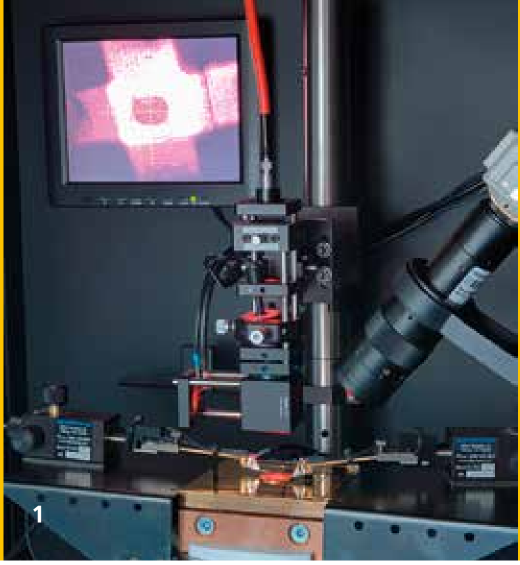
3 *Efficiency values versus irradiance for the two technological routes currently being pursued for AP-MWT solar cells. The concentration factor is with reference to 1000 W/m², corresponding to one sun (C = 1).*

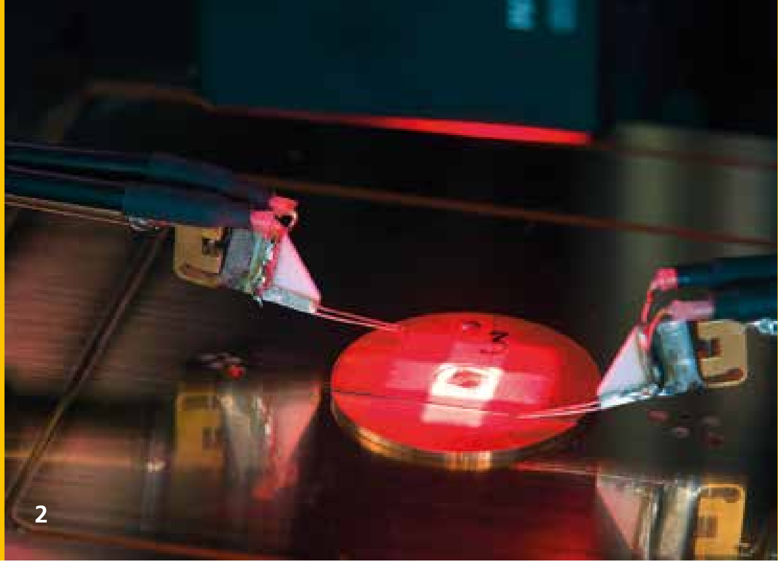
1 *Front and back views of the AP-MWT solar cells on a Si wafer. The examples A to D correspond to possible final solar cell designs after separation from the wafer.*

2 *Schematic cross-sections through AP-MWT solar cells which have been optimized for high (Al-BSF, upper) and low (PERC, lower) irradiance levels.*

The AP-MWT concept features an elementary cell design, which allows cell dimensions from a minimum of 2.25 cm² to a maximum of 189 cm² to be fabricated (Fig. 1). On a single Si wafer, 84 elementary cells are located, which each have an external contact for negative and positive polarity on the back surface. With this configuration, we minimize shading losses due to the front metal grid and maximize flexibility by connections which are made only on the back. With this approach, the current-voltage ratio can be adapted by choosing the appropriate number and dimensions of the cells to be connected. We only use industrially relevant processes to produce the AP-MWT solar cells. Depending on the intended application, technology is used which is particularly suitable for the anticipated irradiance levels. The upper cross-section in Fig. 2 shows a solar cell which has been contacted over the entire back surface (Al-BSF), which is particularly well suited for applications with high irradiance levels. The lower cross-section shows a passivated emitter and rear contact (PERC) solar cell, which is used particularly for irradiance levels of between one and a tenth of a sun.

In the PV-TEC located at Fraunhofer ISE, small series of up to 1000 wafers can be produced, the elementary cells can be separated from the wafers, I-V measurements are made at the required irradiance level and the cells are sorted into performance classes. Furthermore, we offer R&D services concerning connector technology, surface mount technology (SMT) processes, encapsulation and theoretical modelling in addition to electrical characterization of modules.





MONOCHROMATIC CHARACTERIZATION OF LASER POWER CONVERTERS

III-V photovoltaic cells are used not only in solar applications but also for optical power transmission, in which energy is transferred as monochromatic light via an optical fibre. The photovoltaic cell converts the light back to electric power directly at the consumer location. In contrast to the measurement of solar cells with a light source which spectrally resembles the sun as closely as possible, monochromatic radiation is needed for application-relevant characterization of such laser power cells. For this reason, we have established a laser-based measurement set-up at Fraunhofer ISE for calibrated measurement of photovoltaic cells under monochromatic radiation.

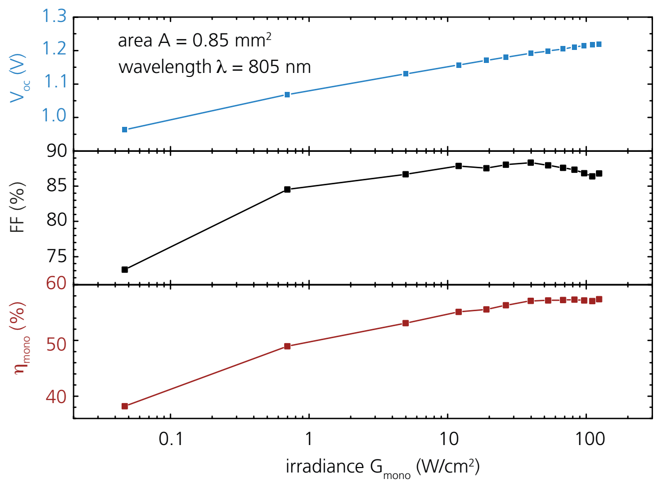
César Garza, **Henning Helmers**, Markus Mundus, Kasimir Reichmuth, Gerald Siefer, Daniel Vahle, Andreas Bett

Optical power transfer can be used to supply electricity to loads (e. g. sensors and actuators) which are located in surroundings where conventional copper cables can cause problems. Examples include high-voltage environments or high magnetic fields, in which galvanic isolation is necessary, avoidance of electromagnetic interference, rotating systems or wireless energy transmission. This technology is used e. g. to monitor wind turbines, in aeroplane tanks, for high-voltage power lines, in smart implants or also to monitor passive optical networks. Very high efficiency values can be achieved by matching the semiconductor material and the laser wavelength. Using GaAs-based cells, we have achieved an efficiency value of 57.4 % for a laser wavelength of 805 nm at an irradiance of 124.0 W/cm².

The accurate and reproducible characterization of photovoltaic cells under monochromatic light, independent of the cell design, poses a challenge. If the test cell is irradiated directly by the laser, the specific prevailing, inhomogeneous beam profile affects the measurement. In addition, the actual laser power must be determined indirectly. The test cell heats up during the measurement if it is irradiated continuously. The measurement set-up which we have established avoids these restrictions. Homogenizing optics is included in the optical path. The intensity is monitored by coupling out part of the beam onto a monitor cell. In addition, the electrical measurement is made during the millisecond of a laser pulse, so that the cell temperature is not raised.

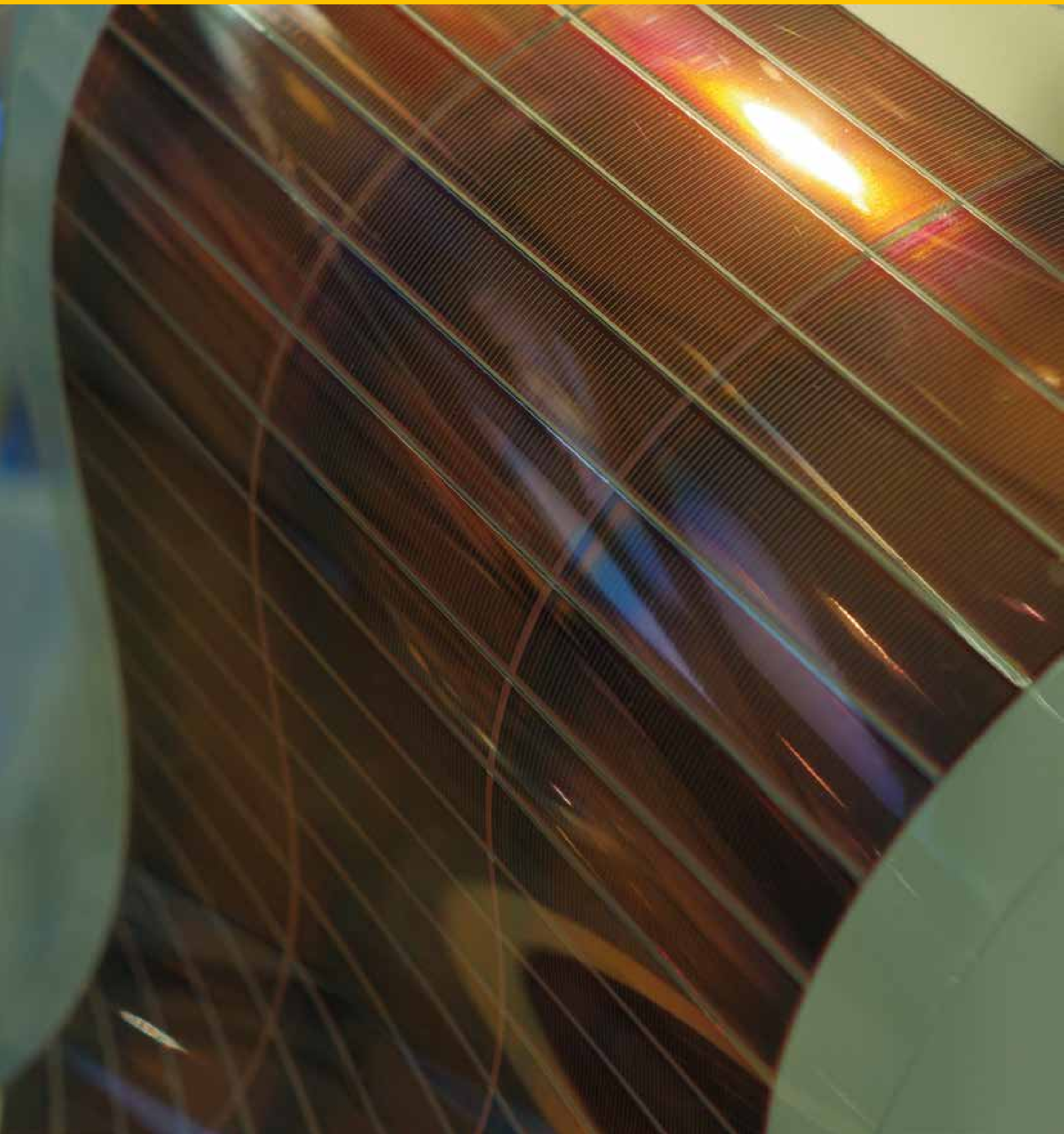
1 *Measurement set-up to determine current-voltage characteristics of photovoltaic cells under monochromatic irradiation.*

2 *Photovoltaic cell mounted on a copper substrate placed in the homogenized beam profile. This enables the characterization to be independent of cell design and alignment.*



3 *Open circuit voltage V_{oc}, fill factor FF and efficiency value η_{mono} of a GaAs-based laser power converter as a function of the irradiance G for monochromatic irradiation at 805 nm.*

DYE, ORGANIC AND NOVEL SOLAR CELLS



Our activities in the area of dye, organic and novel solar cells concentrate on the following topics:

- dye solar cells
- organic solar cells
- photon management
- silicon quantum dot solar cells

The common goal is to reduce the costs for solar energy conversion by applying new technology. Two main approaches are followed: the use of less expensive materials and production processes – particularly for dye and organic solar cells – and the increase of efficiency by improved photon management or new materials, some of which can be combined with different PV technologies.

Large-area dye solar modules are being developed at Fraunhofer ISE for application in photovoltaically active architectural glazing. Research is being conducted on transferring the production concepts to the new area of perovskite solar cells. We have demonstrated that modules can be produced with industrially relevant technology based on screen-printing and new sealing approaches. The 60 cm x 100 cm modules, with durable glass-frit sealing and internal series connection, can be fabricated reproducibly in cooperation with industrial partners. To this purpose, a special in situ coating method was optimized for perovskite solar cells, which requires very little material and can be easily upscaled.

In our work on organic solar cells, we address the whole bandwidth of physical and technological questions concerning organic photovoltaics. This ranges from fundamental understanding of the operating principle of organic solar cells up to the development of cell and module concepts relevant to production. We test and characterize novel organic semiconductors and analyze the efficiency potential on the basis of thorough experimental characterization in combination with optical and electrical modelling. In addition, electrical models enable us to design and optimize different module structures for specific applications. In the laboratory, novel cell and module concepts with a high cost reduction potential are developed and implemented in roll-to-roll processes.

Novel solar cell concepts and photon management encompass the development of concepts, materials and technology to overcome the efficiency limits of conventional photovoltaic technologies and thus reduce the specific costs over the entire value chain. Our activities apply concepts of photon management such as light-trapping structures, upconversion, angular selectivity, spectral splitting and advanced light-trapping concepts. The investigated concepts are generally not restricted to a single solar cell technology but can be applied to already established and also currently emerging technologies.

To make better use of the whole solar spectrum (reduction of thermalization losses), we are also developing silicon-based tandem solar cells. In addition to process adaptation for the Si bottom cell and the development of tunnel contacts, our research is concentrating primarily on new silicon nanocrystalline materials with adjustable band gaps and III-V-based absorber materials. Furthermore, perovskites with suitably adapted band gaps are being investigated for the top cell. The two sub-cells are combined either by direct stack growth on the Si bottom cell or by wafer bonding.

FURTHER INFORMATION

Staff	**45**
Full-time equivalent staff	**31**
Journal articles and contributions to books	**33**
Lectures and conference papers	**18**
Newly granted patents	**1**

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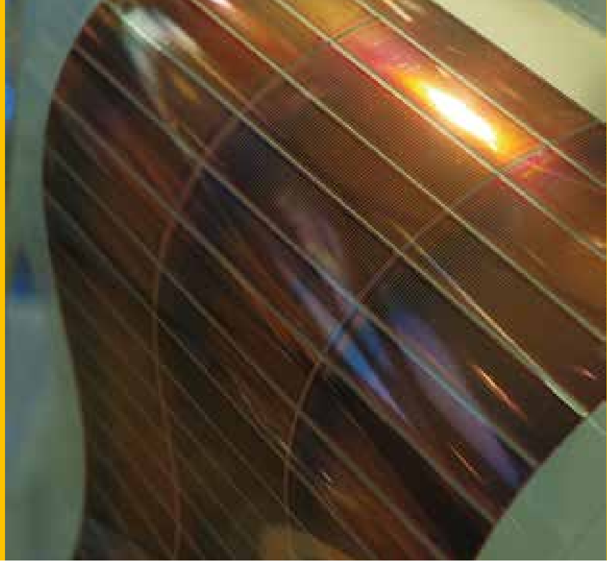

Organic solar module without ITO and with an area of 50 cm x 25 cm.

CONTACTS

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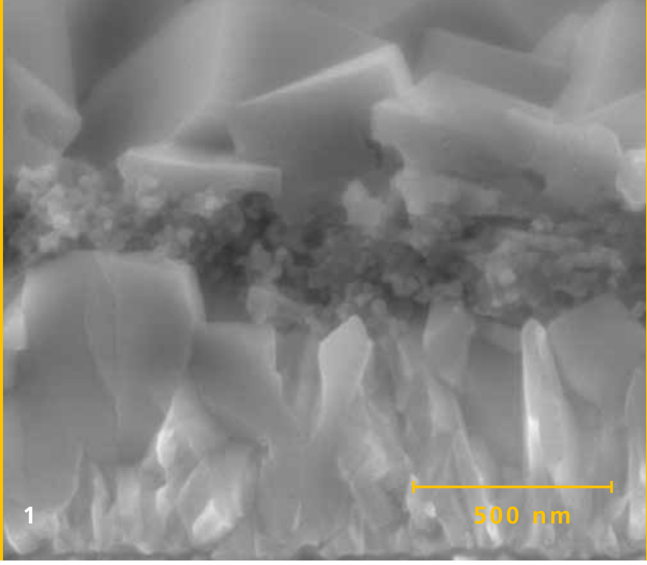
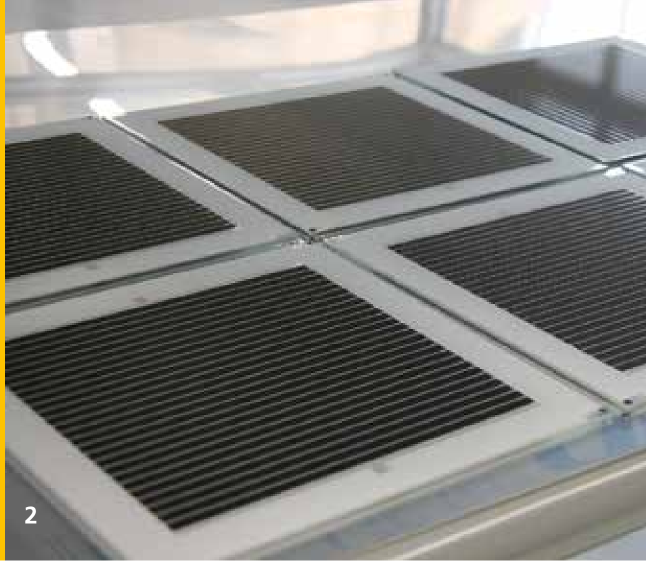




IN SITU PRODUCTION OF PEROVSKITE SOLAR MODULES

In 2014, various research groups announced solar efficiency values of up to 20 % in the laboratory for perovskite solar cells, currently a very active research topic. Fraunhofer ISE is investigating how the principle of perovskite solar cells can be scaled up by a newly developed, in situ coating procedure. In doing so, we draw on our many years of experience in sealing large-area dye solar modules. The solar cells are produced in the interior of a module which has been hermetically sealed by glass soldering. There is no need for vacuum processes or additional lamination. In future, this cost-effective principle could also be applied to other photovoltaic material concepts.

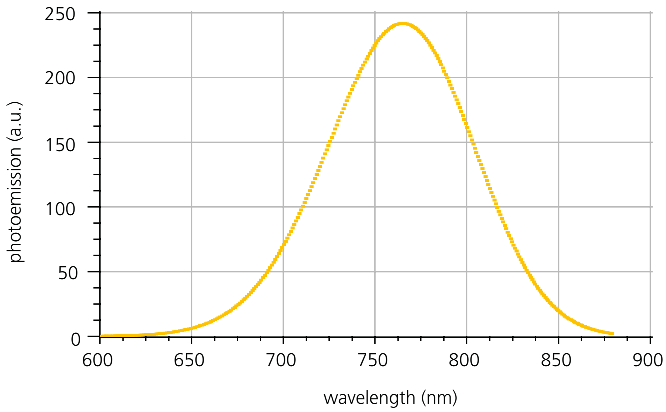
Henning Brandt, Katrine Flarup-Jensen, **Andreas Hinsch**, Simone Mastroianni, Welmoed Veurman, Stefan Glunz

As the photovoltaically very efficient metal halogenide perovskites $CH_3NH_3MX_3$ have the nature of salts, solar cells made of these materials must be very well encapsulated. This is possible with the in situ production process that we have developed. The photoactive materials are adsorbed from solution within the cells by nanoporous substrate layers and deposited during the subsequent drying steps. As our work demonstrated, crystal formation can occur within a few seconds, if the metal salt MX_2 has previously been deposited homogeneously in situ within the electrode layer, and then recrystallization is achieved by introducing the dissolved second perovskite component, CH_3NH_3X. As Fig. 1 shows, perovskite crystals were formed as a continuous photoactive layer and their existence was proven by photoluminescence measurements (Fig. 3). An important step towards efficient, in situ solar cells is optimization of the porous conductive contact layer on the back surface. To achieve this, screen-printing pastes containing graphite were prepared and tested. In addition, we have developed a module configuration with a larger area and printed the first electrode substrates (Fig. 2) with great accuracy.

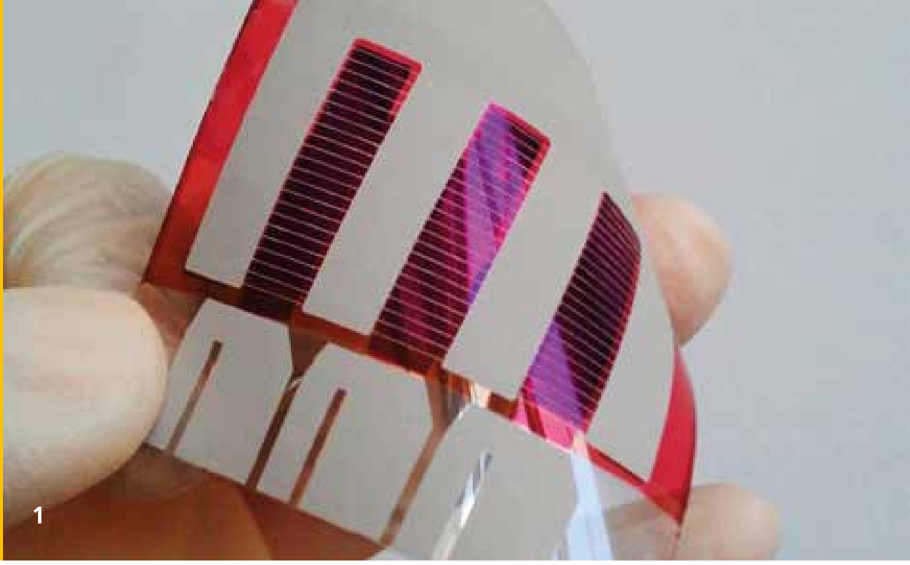
The project work in cooperation with partners from universities and the industry is continuing. The fundamental research was carried out within the European "GLOBASOL" research project.

1 Scanning electron micrograph of the cross-section of a photoelectrode produced in situ for perovskite solar cells on glass. From the bottom to the top of the image, the following zones can be seen: crystals of the transparent, conductive tin oxide, the nanoporous, electron-selective layer of titanium dioxide and the perovskite crystals which were deposited within the solar cell from solution.

2 Screen-printing production of the first electrode substrates for the new development of 20 cm x 20 cm perovskite solar modules according to the in situ process of Fraunhofer ISE.



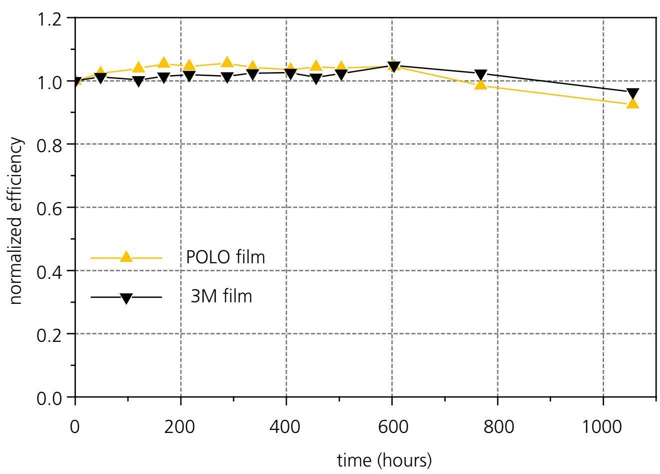
3 The $CH_3NH_3PbI_3$ perovskite, which is currently being used in solar cells, is distinguished by strong photoluminescence in the near infrared. The photoluminescence spectrum, which was measured to prove the existence of the perovskite crystals deposited in situ in the cells, features a characteristic emission maximum at 755 nm.



LIFETIME INVESTIGATIONS OF ORGANIC SOLAR CELLS

Throughout the past years, the efficiency value of organic solar cells has been continuously increased. It now reaches values which make commercial exploitation of this technology appear realistic. In this context, it is important to understand the aging behaviour of organic solar cells. This information can then be used for lifetime predictions. Whereas unencapsulated solar cells quickly degrade when exposed to air and illumination, encapsulated and sealed cells feature much better stability. The efficiency value of our solar cells decreased by only 3 to 10 % of the initial value after exposure to damp heat for 1000 hours. This means that they pass one of the standardized tests for thin-film solar cells.

Ines Dürr, **Markus Kohlstädt**, Subarna Sapkota, Annika Spies, Uli Würfel, Birger Zimmermann, Stefan Glunz



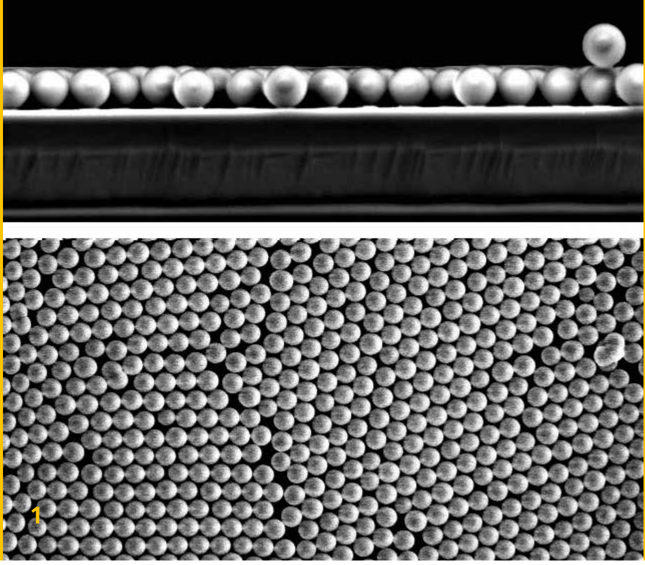
2 Evolution of the normalized efficiency values of flexible solar cells with respect to the initial values during aging under damp heat conditions. The solar cells were encapsulated with barrier films from the Fraunhofer Alliance for Polymer Surfaces (POLO) or from the 3M company.

1 Flexible organic cells on a polymer film substrate, without encapsulation. The active area of the cells is 1.1 cm².

If they are to be commercialized, organic solar cells must demonstrate a lifetime which is appropriate to the intended application. This ranges from approximately three to five years for applications in mobile electronics up to a guarantee for 20 years for building-integrated PV or ground-mounted PV systems. The application areas determine the stress scenarios under which the solar cells in our laboratories are tested.

The degradation of encapsulated organic solar cells is tested at Fraunhofer ISE under an elevated temperature of 85 °C, continuous UV radiation, continuous radiation with an irradiance of 1000 Wm², damp heat (85 °C, 85 % relative air humidity) and under realistic outdoor conditions (weathering). If solar cells are encapsulated, their efficiency value decreases by less than 10 % of the initial value after continuous irradiation for more than 12 000 hours. This corresponds approximately to the radiation dosage to which solar cells in Central Europe are subjected over 12 years outdoors. Thus, a lifetime of more than 20 years is conceivable. Even after 10 000 hours at an elevated temperature of 85 °C, the solar cells suffer practically no loss in power yield. Furthermore, completely flexible solar cells show degradation of less than 5–10 % after 1000 hours of aging under damp heat conditions (Fig. 2). Thus, they passed standard test criteria for thin-film solar modules according to IEC 61646.

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



PHOTON MANAGEMENT FOR EFFICIENT AND COST-EFFECTIVE SOLAR CELLS

Photon management can favourably influence the path and spectral composition of light. At Fraunhofer ISE, we apply photon management to absorb more light in solar cells and to make a wider spectral range useful to solar cells by spectral upconversion. With novel optical nano-structures, we implement solar cells with high absorptance and lower surface recombination losses, and seek to increase upconversion efficiencies.

Alexander Bett, Benedikt Bläsi, Johannes Eisenlohr, Stefan Fischer, Benjamin Fröhlich, **Jan Christoph Goldschmidt**, Johannes Gutmann, Hubert Hauser, Martin Hermle, Barbara Herter, Clarissa Hofmann, Oliver Höhn, Benjamin Lee, Nico Tucher, Sebastian Wolf, Stefan Glunz

1 *Hexagonal grating consisting of self-organized silicon dioxide spheres, which was produced to increase light trapping in solar cells. A monolayer of the spheres is deposited by rotary coating onto a passivated silicon wafer (top); a hexagonal configuration forms in a self-organizing process (bottom). Subsequently, the voids are filled with a material of high refractive index.*

Grating structures on the back surface of silicon solar cells can deflect weakly absorbed light and thus ensure better light trapping. Such grating structures can be produced cost-effectively by imprint processes or by self-organizing processes (Fig. 1). At Fraunhofer ISE, we produce structures which are separated by a passivation layer from the electrically active part of the solar cell. This reduces the surface recombination rate and very high voltages (> 700 mV) become possible. With this approach, sophisticated texturing of the front surface is no longer necessary, saving costs.

"Upconversion" designates the conversion of low-energy photons that cannot be absorbed by the solar cell into higher-energy, useful protons. Together with partners from the University of Pisa, we were able to increase the current of a bi-facial silicon solar cell by 0.5 $\%_{rel}$ by applying a $BaY_2F_8:Er^{3+}$ upconverter. This new record value for upconversion is better than the best value from about four years ago by a factor of 40. To further increase the upconversion effect, we are investigating photonic nano-structures, which concentrate incident light onto the upconverter and favourably influence the emission of light. For example, the upconversion luminescence can be increased by at least a factor of three by grating structures.

Research on photon management is supported by the Deutsche Forschungsgemeinschaft (DFG), the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Affairs and Energy (BMWi).

PHOTOVOLTAIC MODULES AND POWER PLANTS

Module technology converts solar cells into durable products for safe operation in PV power plants. We support product development toward optimal efficiency, reduced costs, enhanced reliability and specialized applications such as building integration. We characterize modules at the highest level of accuracy, analyze their service lifetime and offer comprehensive module testing. The quality of PV power plants is ensured with our accurate yield predictions, comprehensive system testing and exactly determined Performance Ratios during real operation.

The Photovoltaic Module Technology Centre (Module-TEC) is equipped with a wide range of processing and analytical platforms for mounting and connection technology, especially for testing materials, as well as developing products and processes. We apply measurement and simulation to analyze electrical, optical and mechanical effects from the cell to the module. Our scientists transfer developments from the laboratory phase to module pilot production in relevant sample numbers and formats.

The lifetime and degradation behaviour of components in a PV power plant are decisive in determining its profitability. Understanding and identifying the causes of aging is the task of environmental simulation. We observe the behaviour of test objects such as PV modules in detail under different climatic conditions with monitoring equipment that has been developed in house. In addition, we investigate the effect of climatic loads preferably with non-destructive analytical methods (e. g. Raman and infrared spectroscopy) in order to understand aging mechanisms and identify them as early as possible. On the basis of environmental and degradation analysis, we develop simulation models and accelerated testing procedures to investigate aging behaviour, particularly to characterize new materials and components. Not only the equipment of TestLab PV Modules, which has been accredited since 2006, is available for testing, but also special testing facilities for combined loads or accelerated aging, some of them developed in house.

With the four phases of the Fraunhofer ISE quality cycle – yield assessment, module characterization, system testing and performance evaluation – we guarantee comprehensive quality control of PV modules and power plants. Together with good planning and the usage of high-quality components, this is decisive for efficient operation and high yield of a PV system and can thus improve the bankability of the presented concept. In the planning phase of a PV power plant, we draw on reliable radiation and meteorological data and simulate the system configuration exactly. For accurate measurement and characterization of PV modules, our CalLab PV Modules offers different standard and high-accuracy measurements for research, development and production. The CalLab PV Modules at Fraunhofer ISE is one of the internationally leading laboratories in this field, with its measurement accuracy of better than 1.6 % for crystalline modules. Once a PV system is operating, detailed on-site analysis provides information about the instantaneous quality of the system and the real Performance Ratio. Our customized PV monitoring offers accurate analysis of system and component efficiency throughout the complete service life of a PV system.

By combining expertise on the topics of photovoltaics and power supply in buildings, questions relating to the integration of solar energy into buildings can be addressed comprehensively at Fraunhofer ISE. In addition to energy-relevant and architectural aspects, also matters concerning building science, construction and controls technology are taken into account. Detailed modelling of the PV system from the cell to the inverter forms the basis for BIPV module development, total system optimization and system design.

FURTHER INFORMATION

Staff	**115**
Full-time equivalent staff	**84**
Journal articles and contributions to books	**15**
Lectures and conference papers	**21**
Newly granted patents	**2**

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Non-destructive material analysis for PV modules applying Raman spectroscopy. This technology is used to determine the spatial distribution of degradation behaviour due to the polymer encapsulation material of PV modules. It allows degradation indicators for lifetime models to be measured simply and aging mechanisms to be identified.

CONTACTS

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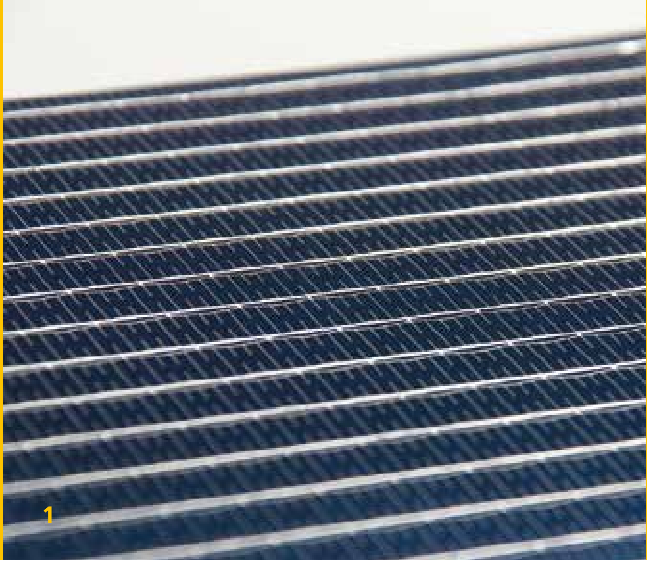
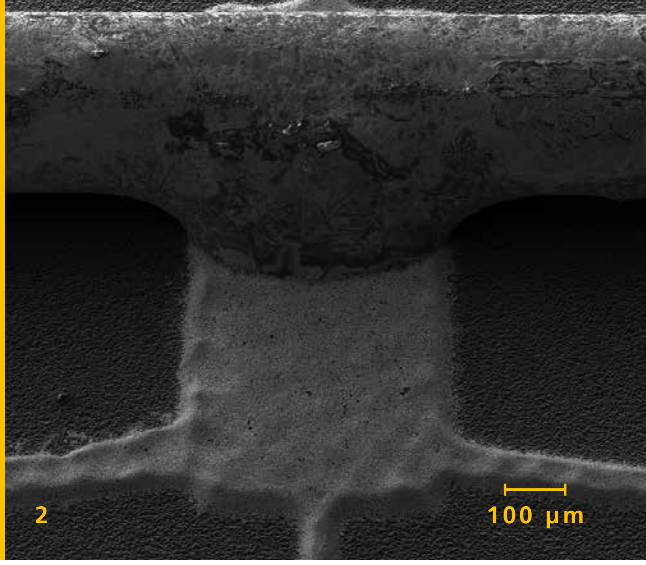




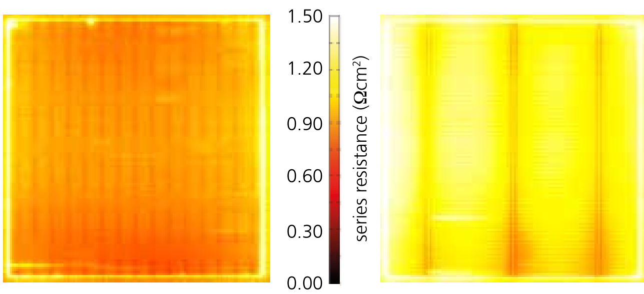
WIRE CONNECTION OF SOLAR CELLS – EFFICIENT AND RELIABLE

Crystalline silicon solar cells are commonly connected today by soldering flat connector strips to the three busbars of the cell. An alternative is connection with thin wires having a circular cross-section. It results in a more homogeneous current distribution over the cell, lower silver consumption for the front contact grid and a higher module power output due to more favourable light reflection. In addition, the numerous thin wires on the cell have a homogeneous, aesthetically attractive appearance. Our measurements show that solar modules with this wire-based connection technology feature very good reliability under accelerated aging conditions and potentially higher efficiency values than standard modules.

Ines Dürr, Ulrich Eitner, Torsten Geipel, **Li Carlos Rendler**, Marco Tranitz, Johann Walter, Harry Wirth

1 *Solar cell with wire connectors.*

2 *Scanning electron micrograph of the solar cell surface. It shows the metallization on the solar cell surface, a wire connector and the joint which formed after the soldering process.*



3 *Spatially resolved, photoluminescence image of the series resistance of a contacted solar cell (left: solar cell with wire connectors, right: solar cell with three busbars).*

In cooperation with the equipment manufacturer, SCHMID, we are developing a new generation of stringers. Here, solder-mantled wires are soft-soldered onto the solar cell. The concept offers the advantages that it can be integrated simply into existing module production lines and that well-established tin-containing standard solders and processes can be used. To date, 50 % silver could be saved by adapting the front contact grid and directly contacting the back-surface aluminium. Further reduction is currently being evaluated. Detailed characterization of the connection point and metallization plays a key role in this development. Thus, the PL-R_S (series resistance photoluminescence) method was further developed and the spatial distribution of the series resistance losses, which had been reduced by 23 %, was quantified. Furthermore, a special preparation method allows the microstructure of the connection points to be analyzed and the cell adhesion to be tested, also after accelerated aging tests. Thermomechanical characterization of the wire is another main aspect of our research. In this way, the connection process was continually improved. The pulling force is significantly higher than 1 N/mm soldered strip width. Critical reliability tests from IEC 61215 to check long-term stability were also passed. It became evident that the solder points feature very good mechanical stability and are able to withstand the loads induced during solar module testing.

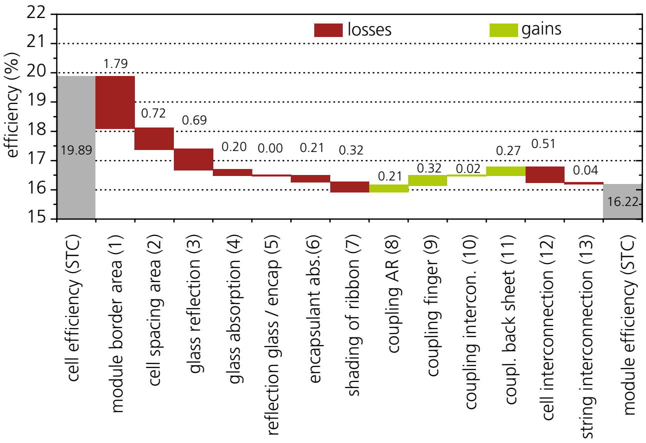
The joint project with the company Gebr. SCHMID GmbH is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

1

MODULE INTEGRATION OF SOLAR CELLS: LOSSES AND GAINS

In crystalline solar modules, connection and encapsulation of the solar cells can lead to power losses on the order of 10 to 20 watts. Detailed understanding of the loss and gain mechanisms is thus decisive to reducing specific module costs (€/W_p). We have developed a methodology which quantifies and differentiates the individual influence of the module materials used and the module design on the total power. It is based on a series of optical and electrical measurement methods which complement each other. The calculation model allows the interaction between optical and electrical effects in the module to be analyzed and enables targeted optimization of module output power and efficiency.

Ulrich Eitner, **Ingrid Hädrich**, Martin Wiese, Harry Wirth



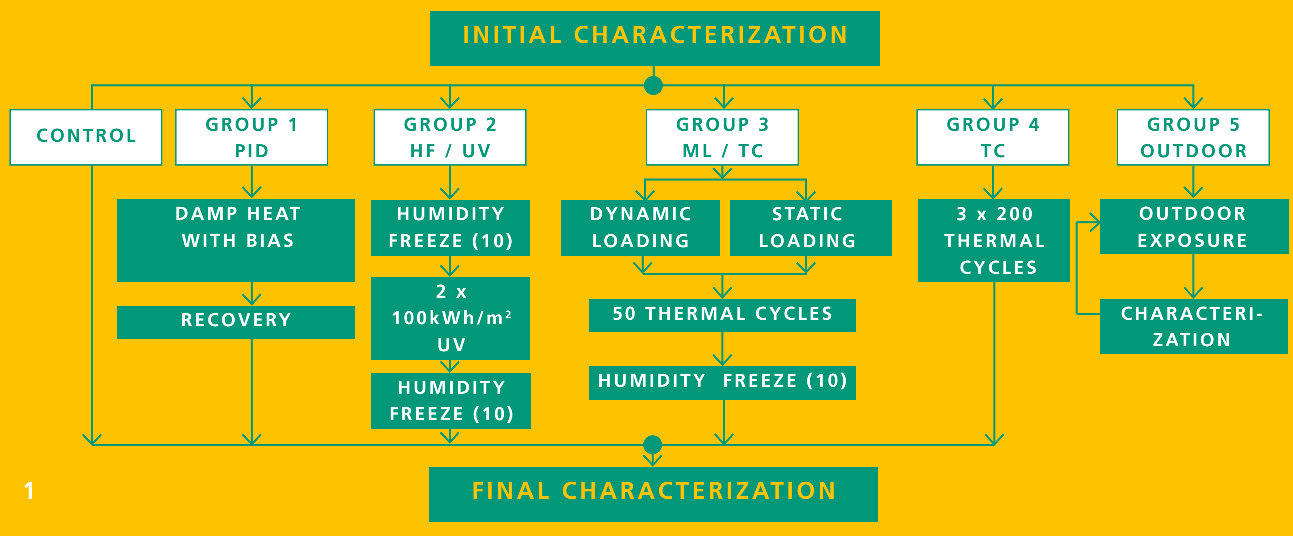
2 *Loss and gain mechanisms calculated for the example of a commercial solar module consisting of 60 monocrystalline, pseudo-square solar cells.*

1 *TopMod module with optimized cell-to-module losses.*

In our model, we differentiate between geometrical, optical and electrical effects. Fig. 2 presents the interacting effects in a clear format. Inactive module area outside the cell area results in geometrically caused efficiency value reduction. Optical losses are caused by reflection and absorption in the cover layers, whereas optical gains result from reflection-reducing changes to the refractive index transition at the cell surface and indirect light reflection from the cell front contact grid, cell connectors and the space between cells. Ohmic resistance in the cell and string connectors is primarily responsible for electrical losses.

We have varied front and back materials and determined the effect on the module power. It became evident that the investigated backing materials can lead to a power gain of 4 to 7 watts by indirect light reflection, while the encapsulation materials cause absorption losses in the range from 1 to 6 watts.

In order to achieve the maximum module power, all of the mentioned effects which affect the efficiency must be considered in a holistic approach. The cell-to-module losses can be minimized by innovative materials such as light-deflecting elements or highly transparent cover materials, as well as by optimal module designs, even to the extent that the yield is greater than that of the original solar cells. Particularly for high-efficiency cell concepts such as bi-facial or rear-contact solar cells, balancing the cell-to-module losses is important with regard to efficient connection and yield-optimized encapsulation.



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PHOTOVOLTAIC MODULE DURABILITY INITIATIVE (PVDI)

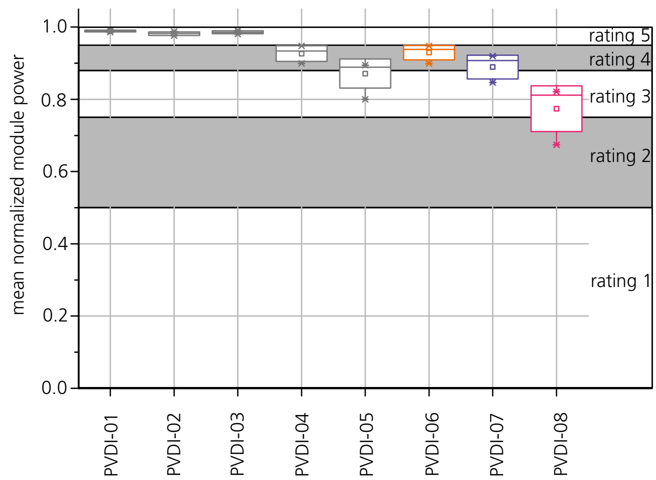
PV modules are predominantly tested and certified according to the relevant IEC standards (IEC 61215, IEC 61646 and IEC 61730). These tests thus establish a uniform basic quality standard throughout the world. Nevertheless, defects and faults are observed in the field also for certified PV module types. In addition, fault modes occur in the field, which are not the subject of tests in the current versions of the IEC standards. Fraunhofer ISE and Fraunhofer CSE (USA) have developed a comparative testing programme within the "Fraunhofer PV Module Durability Initiative" (PVDI), which goes beyond the currently valid IEC standards and includes currently observed failure modes.

Claudio Ferrara, Georg Mülhöfer, Daniel Philipp, Sandor Stecklum, Harry Wirth

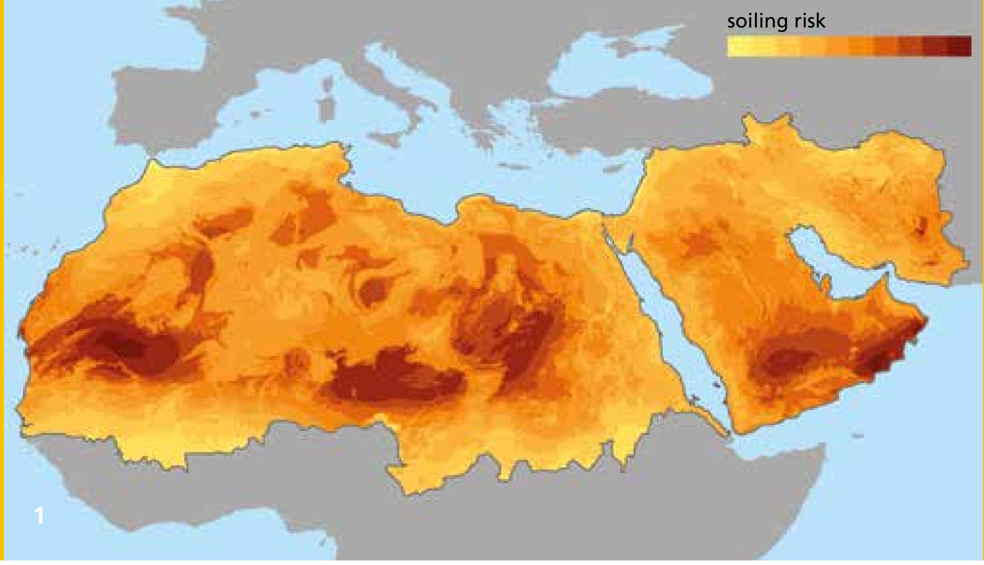
For the Fraunhofer PVDI programme, the PV modules to be tested are mainly purchased on the free market. After initial characterization, 16 such modules are currently divided out among four laboratory testing sequences as well as monitoring at the Albuquerque site in New Mexico, USA. First, the sensitivity of the PV modules with respect to potential-induced degradation is investigated. The test is repeated three times, interrupted by intermediate characterization and ended with a recovery phase. In the second test sequence, the reaction of the PV modules to humidity-freeze cycles and to UV radiation is investigated. In the third test sequence, the resistance of the test samples to cyclic and stationary mechanical loads at low temperatures is examined. The temperature cycling is intended to make the propagation of defects visible. The fourth test sequence serves as a reference for the temperature cycling test with 200 cycles from the IEC standard, but then goes beyond this with a total of 600 cycles. Of the three PV modules which are exposed outdoors for three years in New Mexico, we continuously record the performance data for one PV module. The performance of all three test samples is measured in the laboratory every six months under standard test conditions.

Since 2011, eight types of PV modules from eight different manufacturers have been tested in the Fraunhofer PVDI programme. For each test sequence, the module type is classified between 1 (lowest class) and 5 (best class), based on the normalized module power after weighting with the final measurement (Fig. 2).

1 *Schematic representation of the comparative test programme within the framework of the Fraunhofer PV Module Durability Initiative (PVDI).*



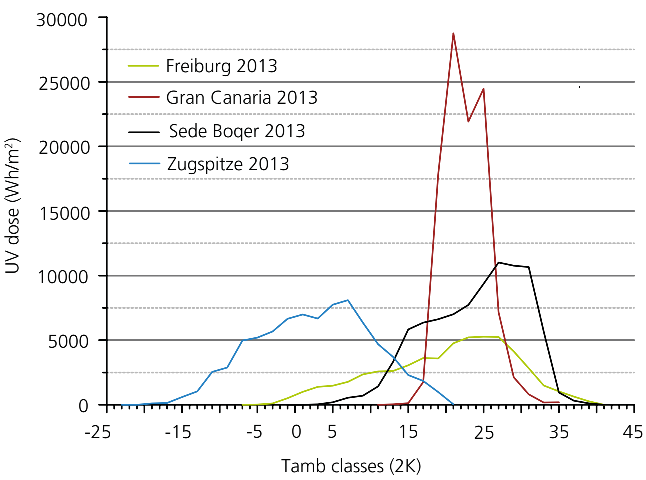
2 *Classification of the tested PV modules after the dynamic mechanical test.*



MAPPING AND CLASSIFICATION OF PV MATERIAL WEATHERING LOADS

Materials and components of PV modules are exposed to different weathering effects, which have a major influence on the lifetime and performance of the systems (Fig. 2). In future, more regions with harsher climatic conditions will be considered for PV installations. However, at present there is a lack of concrete information on the meteorologically and environmentally induced risks for PV systems. Global classification of the prevailing stress conditions is necessary for the selection of optimal materials and to estimate the lifetime of PV systems. Fraunhofer ISE has developed a suitable spatial classification system for site-dependent stress conditions with the help of a Geographical Information System (GIS).

Jan Herrmann, Michael Köhl, Christian Schill, **Karolina Slamova**, Karl-Anders Weiß, Harry Wirth

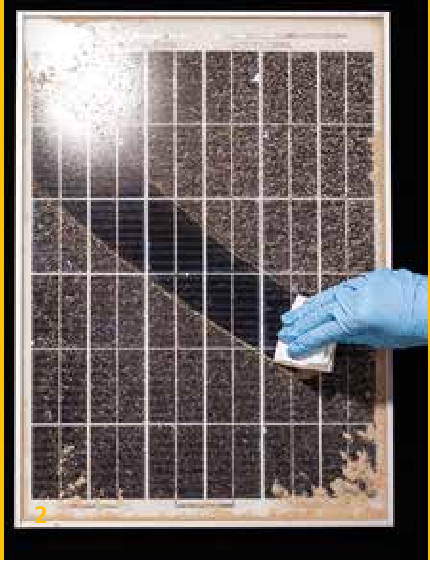


2 *Characteristic frequency distributions for the combined loads due to UV radiation and ambient temperature (Tamb) at four outdoor weathering test facilities belonging to Fraunhofer ISE.*

1 *GIS-based map of the qualitative soiling risk in the Middle East and North Africa (MENA region) on the basis of global satellite data and historical, ground-based meteorological measurements.*

Loads on materials and components that are caused by various environmental influences are important factors determining the lifetime and performance of PV modules. Premature material degradation and power losses affect the yield and levellized cost of electricity negatively, and thus affect the ecological and economic sustainability of solar energy conversion. UV radiation, high temperatures, relative air humidity, condensation duration, humidity and heat cycles, atmospherically induced corrosion, soiling and moisture penetration have been identified as critical load factors for PV. Typical degradation effects include the yellowing of polymer encapsulation materials, the delamination of the encapsulation layers and backing sheets, and the corrosion of connection components.

In order to estimate the lifetime of solar technical components in locations around the world and to sustainably improve the materials used, Fraunhofer ISE has developed a spatially resolved, GIS-based stress classification system. This allows site-specific loads already to be taken into account during the development and planning phases. A spatially resolved, global stress classification system offers important information to material manufacturers and other stakeholders such as system planners, insurance companies and investors. Research work such as mapping the soiling risk in the MENA region (Fig. 1), the analysis of corrosion in coastal regions or the classification of UV loads are important components in such a comprehensive stress classification system.



DETERMINATION OF SOILING EFFECTS AND TESTING OF COATINGS

Sunny desert regions, for example those in the Middle East and North Africa (MENA region), are increasingly attracting the attention of the PV industry. Under the conditions prevailing there, dirt particles adhering to surfaces – so-called "soiling" – cause substantial losses in PV yield. This effect is increased by proximity to the sea, condensation on surfaces at high air humidity and temperature fluctuations. To estimate the service life of PV modules, an understanding of the interactions between dirt and other materials is fundamental. Climate modelling (based on GIS), accelerated aging tests and realistic soiling tests help to qualify counter-acting measures such as functional coatings and to investigate their long-term stability.

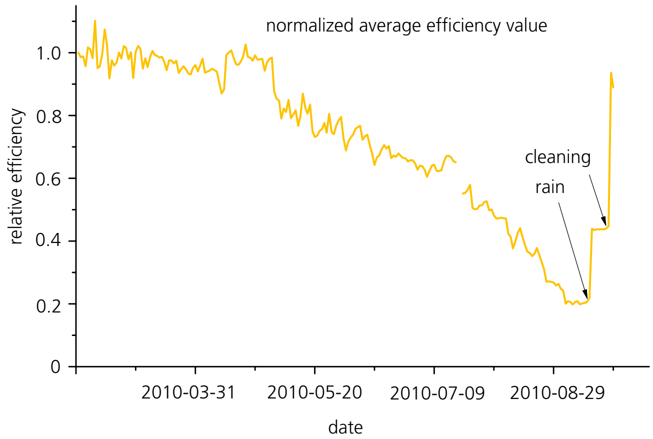
Jan Herrmann, **Elisabeth Klimm**, Michael Köhl, Timo Lorenz, Daniel Philipp, Christian Schill, Karolina Slamova, Karl-Anders Weiß, Harry Wirth

Inorganic materials such as sand and dust adhere to surfaces and lead to yield reductions, particularly in desert regions. In the worst case, the material surface is additionally damaged by chemical reactions or abrasion by sharp-edged particles. The chemical and physical properties of the sand, just like the climatic conditions, depend strongly on location and decisively affect its behaviour in soiling surfaces.

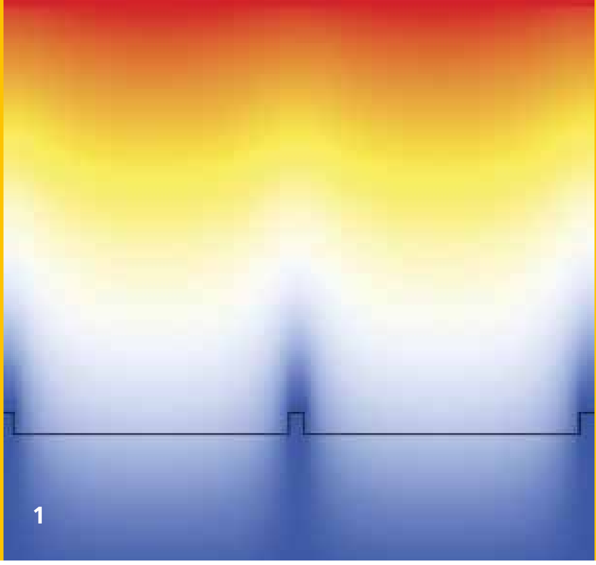
Meteorological monitoring by Fraunhofer ISE allows load and climatic data to be analyzed and presented in soiling risk maps based on Geographical Information Systems (GIS). On the basis of the climatic data and technological criteria, special testing facilities and test sequences were developed which allow the surfaces of glazing materials and special coatings to be investigated with regard to their soiling behaviour. In doing so, realistic conditions such as dry or moist sand can be created by the usage of locally typical sands and climatic conditions. The evaluation is based on the spectral transmittance reduction due to soiling and the amount of deposited material. These measurements are complemented by durability tests of the surfaces to ensure their long-term functionality. The results are used to define optimal cleaning strategies and to determine the economic viability of coatings.

1 PV modules at the outdoor test field of Fraunhofer ISE on Gran Canaria.

2 Soiling on a photovoltaic module used to measure the power losses due to dust and sand.



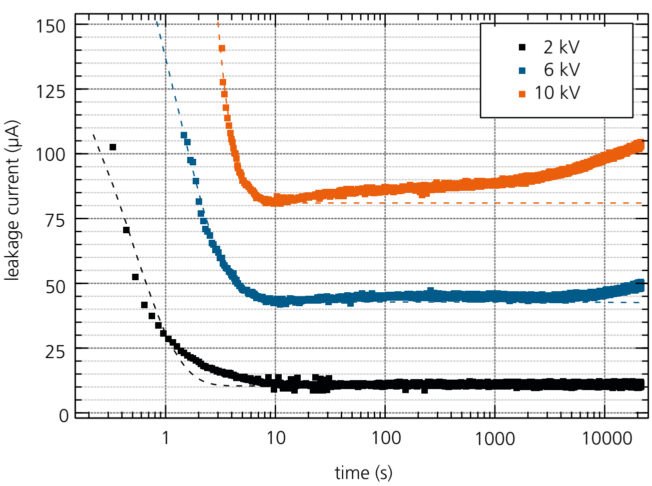
3 Reduction of the average efficiency value of different module types by 80 % within eight months due to soiling. Rain in September 2010 removed some of the dirt; complete cleaning was subsequently carried out by service staff.



CHARGE TRANSPORT IN SOLAR MODULES UNDER HIGH VOLTAGE LOADS

Even in recently installed PV systems, solar modules can be found which have suffered power losses due to Potential-Induced Degradation (PID). Fundamental understanding of the PID effect – particularly of the occurring electric field distributions and the leakage currents in a module during a high voltage load – is needed for long-term material improvements. Measures to prevent PID, such as altered designs, encapsulation materials with lower ionic conductivity and modified front glass covers, were tested. We have developed a simulation programme to model the electric field distribution in real solar modules and investigated leakage currents with a special high-voltage measurement stand.

Stephan Hoffmann, **Thomas Kaden, Michael Köhl**, Hans Joachim Möller, Andreas Bett, Harry Wirth



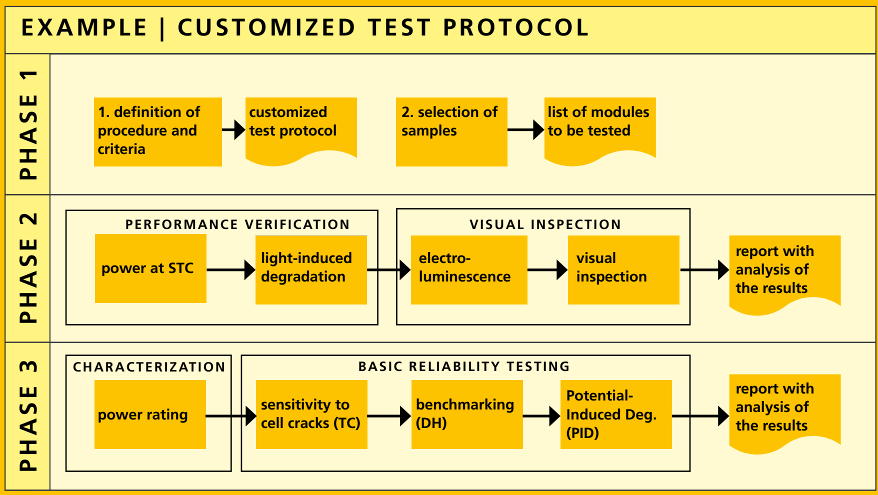
3 *Time-dependent leakage currents at different test voltages in a multicrystalline silicon solar module with a strong PID effect.*

1 *Simulated electric field distribution through the cross-section of a solar module under high voltage conditions. The image shows two contacts on a solar cell.*

2 *High-voltage measurement set-up in the Technological Centre for Semiconductor Materials in Freiberg. Test voltages of up to 20 kV can be applied.*

Fraunhofer ISE has developed a process which allows cells that are susceptible to PID to be produced deliberately and reproducibly. Using these cells, we have compared PID-hindering measures at the module level. The laminates were tested at conditions deviating from those specified in the IEC draft standard. They were covered with conductive aluminium foil; the potential difference amounted to -1 kV DC. The temperature was raised to 60 °C, whereas the duration was shortened to 16 h. This resulted in an acceleration factor of about 2.5 compared to the 25 °C/168 h test. Whereas the reference design V01, which had been classified as "sensitive", showed clear PID, all of the other variants remained stable. The TPedge module developed at Fraunhofer ISE proved to be stable with respect to PID. Furthermore, we tested a specially treated glass pane with a coating deposited to act as an ionic diffusion barrier. Laminates fabricated with this glass showed clearly reduced leakage currents and much lower PID.

To investigate leakage currents in greater detail, the Technology Centre for Semiconductor Materials in Freiberg used a special high-voltage test set-up, which can create test voltages up to 20 kV. This allows the PID effect to be clearly intensified and also reveals very small effects on the leakage current, such as ionic transport out of the module glass cover. Theoretically, the initial profile of the time-dependent leakage currents can be described as a capacitive charging current within the module. An additional component became evident for longer test durations. It started earlier for higher voltages (Fig. 3). The additional charge correlates with the power loss.



1

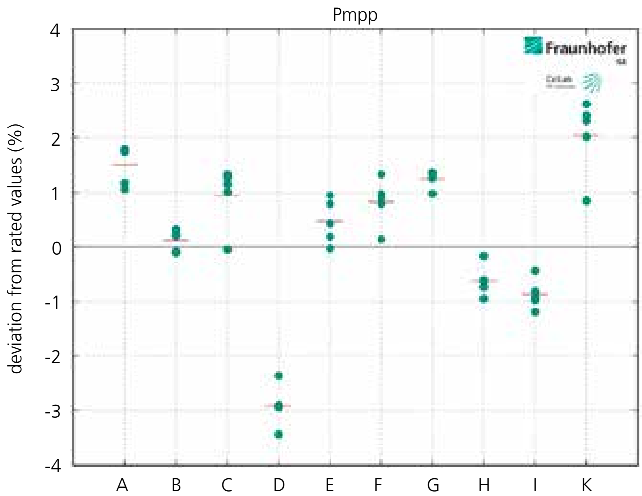
QUALITY BENCHMARKING OF PV MODULES

"Quality benchmarking" is a procedure developed together with project planners and distributors for PV module testing that has been optimized with regard to time and costs. It meets the demand, in a very dynamic market with rapidly changing product variants, to gain information in the shortest time possible about the quality of a selected charge of a given module type. Based on the clients' quality specifications and the application areas of the modules, we define an individual testing procedure and pass / fail criteria. The procedure allows objective evaluation of the modules, independent of the manufacturer. For our clients, quality benchmarking is thus a central component of their quality control strategy.

Boris Farnung, Klaus Kiefer, Frank Neuberger, Daniel Philipp, Harry Wirth

Fig. 1 shows an example of a customized testing procedure with different testing phases. After defining the procedure and choosing the random sample in Phase 1, we check the electrical parameters specified by the manufacturer (data sheet and model label specifications) in Phase 2 and also visually inspect the external appearance of the components used (frame, plugs, connection box, soldered connectors, etc.), also noting the quality of workmanship. The first tests serve to select the so-called "best of class", those module types which have qualified or met the criteria on the basis of the initial results. Test samples which do not meet these previously defined quality criteria are not investigated further. In this way, costs for the more expensive tests belonging to Phase 3 are saved. The power rating measurements which are recommended for Phase 3 also simultaneously provide the required input data for accurate yield predictions. In this phase, the modules are also tested for their susceptibility to cell breakage and snail trails, properties that are important for long-term reliability.

1 *Example of a customized testing procedure.*



2 *Example for the evaluation of the module performance of ten different module types within a quality benchmarking procedure. The comparison reveals some appreciable deviations among the different module types concerning the actual module power and the specified rated power.*

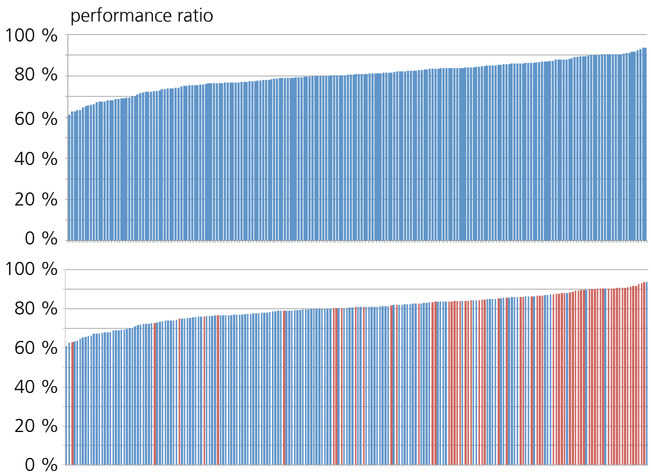
In addition, further reliability and material tests can be carried out which take account of the specific operating conditions at the planned system location or special features of a relevant module technology.

The quality benchmarking procedure with the described tests provides well-founded information about the performance and fabrication quality of the tested products within a few days and identifies deviations from the state of the art. Degradation mechanisms and product defects are identified by the reliability tests. Furthermore, the risk of faults occurring in the field is minimized.

QUALITY STANDARDS FOR THE BANKABILITY OF PV POWER PLANTS

Investment decisions for PV power plants are usually based on the anticipated levellized cost of electricity (LCOE). A reliable LCOE prediction for new or existing power plants demands high quality standards. Quality assurance measures can be derived from the input parameters for LCOE calculations, which ensure that the expectations of banks and investors are met. In a benchmarking exercise on 300 of the PV power plants monitored by Fraunhofer ISE for 2014, it became evident that PV power plants which are subject to such quality assurance measures achieve significantly higher yields and good long-term performance. Based on these benchmarking results, we have cooperated with partners to define new quality standards to evaluate PV power plants.

Boris Farnung, Klaus Kiefer, Björn Müller, Harry Wirth

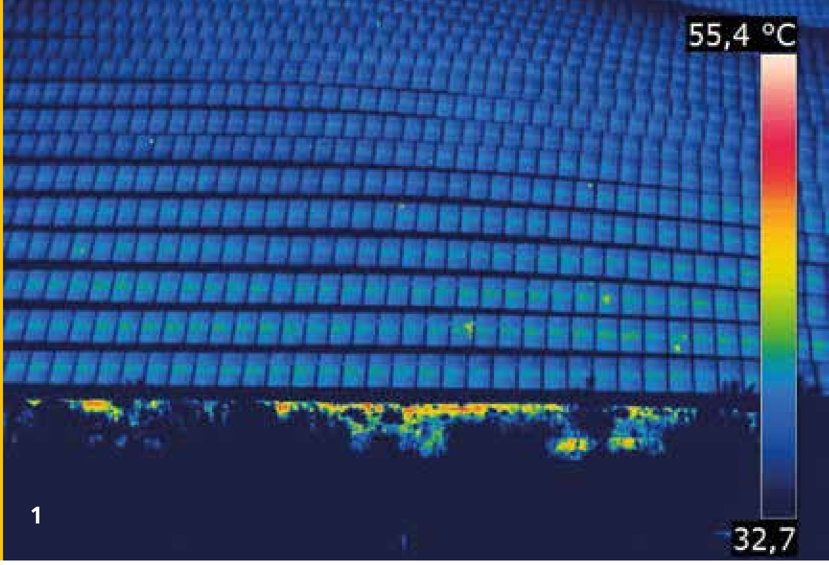


2 *Annual benchmarking exercise for the Performance Ratio of 300 PV power plants based on performance in 2014. In the bottom graph the red lines indicate power plants subject to quality assurance by Fraunhofer ISE.*

1 *The Lieberose Solar Park near Cottbus, Germany.*

An important indicator for the quality of a PV power plant is the levellized cost of electricity (LCOE). The LCOE for power plants in Europe today is typically in the range from 0.08 to 0.12 €/kWh. Important technical input parameters to calculate this value include the initial Performance Ratio (PR), the initial module efficiency value, the irradiance on the module plane and the annual power reduction rate for the PV plant. Quality assurance measures can be derived for all of these input parameters, which ensure that the expectations of banks, investors and insurance companies are met. These expectations differ, depending on the perspective of the project stakeholders. The project developer and the later operator of the power plant aim for the best possible performance at low maintenance levels. The financing bank is interested in repayment of the loan over the agreed term, and the investor expects the highest possible return at low risk.

In a benchmarking exercise on 300 of the PV power plants monitored by Fraunhofer ISE for 2014, it became evident that PV power plants which are subject to continuous quality assurance measures achieve significantly higher yields and good long-term performance. For this reason, and due to the increased interest in evaluation of existing power plants, Fraunhofer ISE has added further quality assurance measures to its service portfolio – such as manufacturer-independent energy ratings for PV modules, power plant certification in cooperation with the VDE, validation of in-house power plant monitoring and performance evaluation on the basis of measured data.



REPOWERING PHOTOVOLTAIC POWER PLANTS

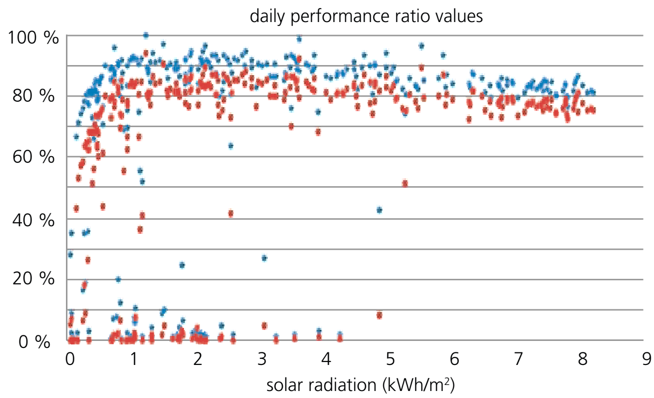
With the amendment to the German Renewable Energy Act in 2004 and the resulting acceleration in PV power plant installation, the installed PV power in Germany exceeded the GW limit. As a consequence, the number of power plants which have been operating for more than ten years is increasing continuously. The yield from these installations can deviate significantly from the yields that are possible today for a variety of reasons. Partial renewal of a PV power plant – also termed "repowering" – can raise the level again to that of a newly installed system. To prepare such a measure, its effectiveness and thus the economic feasibility must be assessed individually. We offer our support for such processes.

Klaus Kiefer, **Christian Reise**, Harry Wirth

As the first step, the actual operating results from the most recent year are compared with calculated values within a Performance Ratio evaluation. If it is available, the yield prediction from the plant planning phase provides the first values for comparison. We make a new calculation of the yield expected from the real, installed system for the past year – taking module degradation since commissioning of the power plant into account. Finally, we repeat the simulation with data from PV modules and inverters which are available today. More extensive changes in the plant design (module tilt, distance between rows, installation configuration) can also be taken into account. However, their implementation is seldom economically viable.

After completing these steps, a large amount of data is available on yields, component behaviour and Performance Ratio, from which we can then specifically derive the greatest potential for improvement. Replacing the inverters is often an option which both improves the efficiency value and the availability of the system. Reconfiguration of the module cabling can change the DC voltage level advantageously – to better match a new inverter. Finally, conspicuously poor PV modules can be replaced. Replacement of individual modules is an obvious option for singular defects (glass breakage, broken cells, defects in the junction boxes). Individual test on site (visual inspection, power measurements, thermographic images) provided the information needed for a replacement plan.

1 *Thermographic image to identify conspicuously poor modules.*

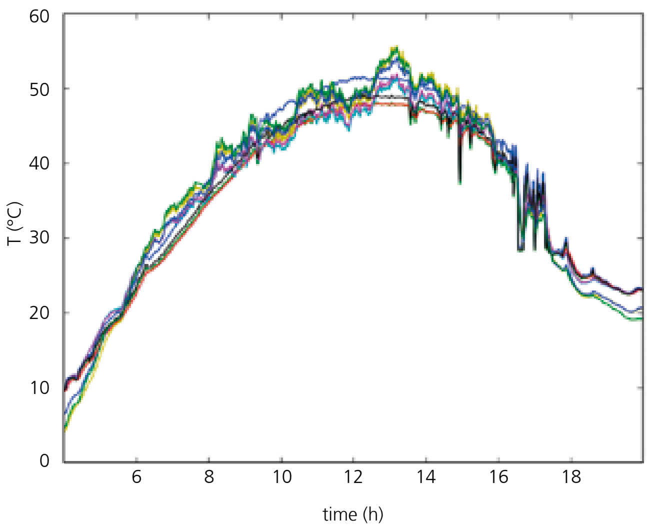


2 *Comparison of the daily Performance Ratio values before (red) and after (blue) exchanging inverters. 6 kW inverters from 2006 were replaced by current 20 kW units. The system efficiency value increased by about 6 % as a result.*

SIMULATION OF THE OPERATING TEMPERATURE OF BIPV SYSTEMS

Building-integrated photovoltaic systems (BIPV) consist of building components which generate electricity photovoltaically. By contrast, BAPV systems (building-applied photovoltaic systems) are composed of PV elements which are "appended" to the building, e. g. PV modules on roofs. In many BIPV applications, the system operating temperature plays a major role for the construction design. In the European "SOPHIA" project, different approaches were applied to simulate the operating temperature of a BIPV system. The results from four European research institutes were compared with the measured temperatures of a BIPV system and the effects on the variation of the yield with time were investigated.

Tilmann Kuhn, **Wendelin Sprenger**, Hans-Martin Henning



2 *Measured (dark blue) and different simulated (all other colours) module back-surface temperatures of a monitored, rear-ventilated BIPV system with 15° tilt, south orientation and installed at CEA/INES in Chambéry, France. Agreement between the simulated and measured module back-surface temperature profiles was quantified by the statistical measures, R^2 and RMSE.*

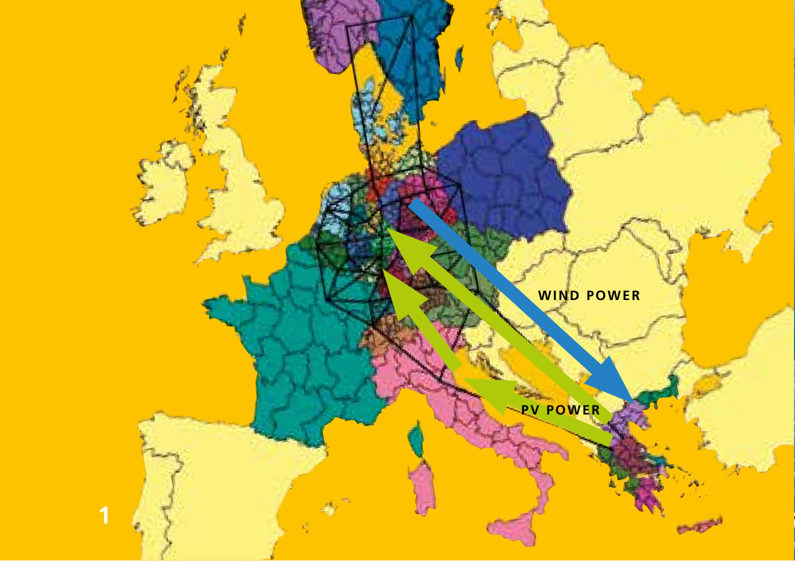
1 *BIPV test stand of CEA, which was the object of the simulation exercise.*

Falling prices for photovoltaics and new EU building regulations have strongly stimulated interest in BIPV in recent years. Economic comparisons with the building components they can replace show that BIPV systems are competitive. However, the existing cost reduction potential must still be exploited, e. g. by simplified authorization procedures and mass production. For BIPV elements which provide the functions of water-tightness or thermal insulation and thus have a significantly reduced heat transfer from the back of the photoactive layer, the operating temperature profile must be calculated. The European "SOPHIA" research project provided a framework to compare the simulation programmes from different European research institutes. Based on the monitoring data of a suitable BIPV system, the effect of raised temperatures on the total yield of the system was validated and analyzed.

For comparison, also simpler simulation approaches were applied. The linear model and the NOCT model (Normal Operating Conditions Temperature) use only irradiance measurements and the outdoor temperature as input parameters. The most complex model used takes account of the sky temperature, wind speed and direction, internal module structure and the heat capacity of the individual layers. The level of simulation detail was increased at Fraunhofer ISE, and used to demonstrate that the heat capacity for BIPV insulating glazing and the variable interior and exterior transfer for rear-ventilated façades must be taken into account.

This project was supported by the European Union within its 7th Framework Programme.

www.sophia-ri.eu



THE ROLE OF PV POWER PLANTS IN THE EUROPEAN ENERGY SYSTEM

The reduced levellized cost of electricity and the rising number of PV installations in many European countries have increased the significance of PV for the public power supply. With a model-based analysis of future electricity generation structures and transmission grid infrastructure, we are investigating the effect of the increased number of PV systems throughout Europe and their interaction with other forms of generation technology and existing grid transmission lines. In the "RES-DEGREE" project we are analysing the effects of increased usage of PV in Germany and Greece, as well as the potential exchange of electricity between these two countries via transit countries. In addition, the "RESlion" model allows an optimal geographic distribution of PV systems for the future to be investigated.

Niklas Hartmann, **Christoph Kost**, Charlotte Senkpiel, Thomas Schlegl

The electricity generation structure of many European countries is currently in a transitional phase due to the expansion of wind and solar power plants and the accompanying increase in electricity generated from renewable energy sources. Our model-based energy system analysis is able to represent PV power plants, other renewable energy systems and the entire energy system in detail. Due to the additional inclusion of Geographic Information Systems (GIS), the potential of the individual types of technology can be determined on the basis of detailed geographical information and taken into account. With this model, Fraunhofer ISE is making an important contribution to optimal planning of further power plants based on renewable energy in national energy systems – also taking more strongly coordinated EU energy policies into account.

1 *Modelled regions of RESlion to investigate the optimal expansion of electricity from renewable sources, its generation and transmission within Central Europe and to and from Greece.*

2 *In many European countries, the electricity generation structure is being transformed toward increasing usage of renewable energy sources. With our models, we can represent complete energy systems.*

Fraunhofer ISE is particularly addressing the question about which PV generation capacity in which regions would be advantageous for the entire electricity system and how these plants should be operated. The question is also investigated with a view as to how different European countries can be connected to increase the exchange of electricity from renewable energy sources across national borders.

Fig. 1 illustrates a detailed model of Germany (at a regional level), its neighbouring countries and Greece. Potential electricity flows between Germany and Greece – taking account of optimal, cost-effective planning of expansion and operation management of conventional and renewable power plants – and the capacity for transmission between the regions can be investigated using the model and the economic viability analyzed.

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

SOLAR THERMAL TECHNOLOGY

In the present energy transformation, solar thermal energy is also a central component. Internationally, the role of solar thermal energy depends both on cost developments in production and distribution, and also on the boundary conditions and market demands that are specific to each country. Research and development can lead to more cost-effective materials, manufacturing processes and total systems which are optimized with regard to investments and yield.

Solar thermal, flat-plate and evacuated tubular collectors today are reliable standard products which need quality assurance and certification to compete on the market. We have offered such services for many years in our TestLab Solar Thermal Systems. By participating in standardization work and the Solar Keymark initiative, we define the guidelines for innovative products. For example, we contributed our experience with air-based collectors and combined photovoltaic and thermal (PVT) collectors in defining appropriate tests for standards. Our Institute also leads in developing a diverse set of tests for linearly concentrating collectors with operating temperatures from 150 °C up to 550 °C and supports product optimization. Different specifications must be met for applications in large solar thermal power stations and in generating processing steam.

We have developed durable, selective absorber coatings and transferred them to industrial production for many years now. With the goal of reducing costs, we are also investigating alternatives to aluminium and copper, e. g. steel, but also non-metallic materials such as ultra-high performance concrete and polymers. This approach leads to completely new construction and production options for solar thermal collectors.

With our technology portfolio for decentralized water purification, we not only construct completely autonomous systems which are optimized for the prevailing water quality but are increasingly applying our expertise to the separation of industrial materials systems.

Systems technological questions such as hydraulic optimization, intermittent operation management and storage integration are decisive for the functioning and economic viability of large solar thermal systems, ranging from domestic hot water heating to solar thermal power stations. We are thus continually expanding our comprehensive dynamic simulation platform and adding new components. Data from monitoring and demonstration projects are used for validation. With the extension of our polygeneration laboratory in 2014, we took a further step toward an experimental system testing centre.

Fraunhofer ISE possesses expertise ranging from materials science, component design, testing and measurement procedures, theoretical modelling and simulation, up to systems technology for the different applications.

Special facilities for solar thermal technology:

- 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, imaging methods, fringe reflectometry, concentrator optics
- thermal technological laboratory to measure the transient behaviour of thermal power generators (up to 50 kW_{el}) and high-temperature storage units
- testing laboratory for membrane distillation, including the stability of components to seawater exposure, and a water laboratory
- TestLab Solar Thermal Systems: certified solar thermal testing laboratory for collectors and systems according to Solar Keymark

FURTHER INFORMATION

Staff	**93**
Full-time equivalent staff	**73**
Journal articles and contributions to books	**14**
Lectures and conference papers	**32**

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© Industrial Solar

Linearly concentrating Fresnel collector.

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LEARNING FROM OTHER BRANCHES: FROM HEATING RADIATORS TO SOLAR ABSORBERS

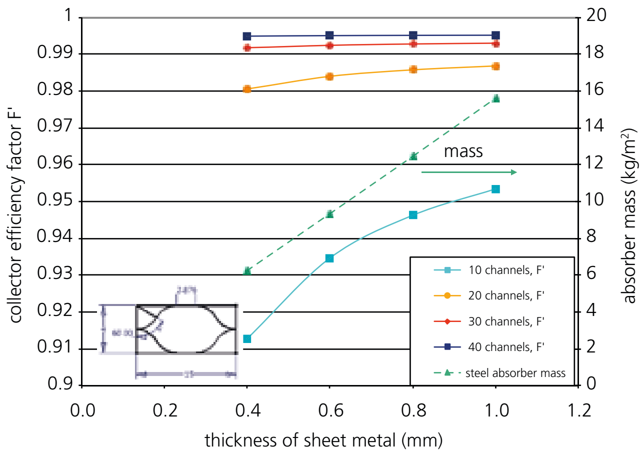
Alternative materials and manufacturing technology offer a great potential for saving costs for solar thermal absorbers. Aluminium or steel can be used instead of copper. Conventionally applied plate-and-piping constructions can be replaced by mass-produced, integrated absorbers. Sheet forming processes enable even poor heat conductors such as steel to achieve good thermal efficiency. Together with our industrial partner, Gräbener Pressensysteme GmbH & Co. KG, we are adapting the embossing and stretch-forming process used today for manufacturing heating radiators to produce solar absorbers of aluminium and steel. We deposit spectrally selective coatings onto the 2 m² absorber plates, which have already been produced, and measure their physical properties.

Michael Hermann, Carmen Jerg, Franziska Kennemann, **Lotta Koch**, Werner Platzer

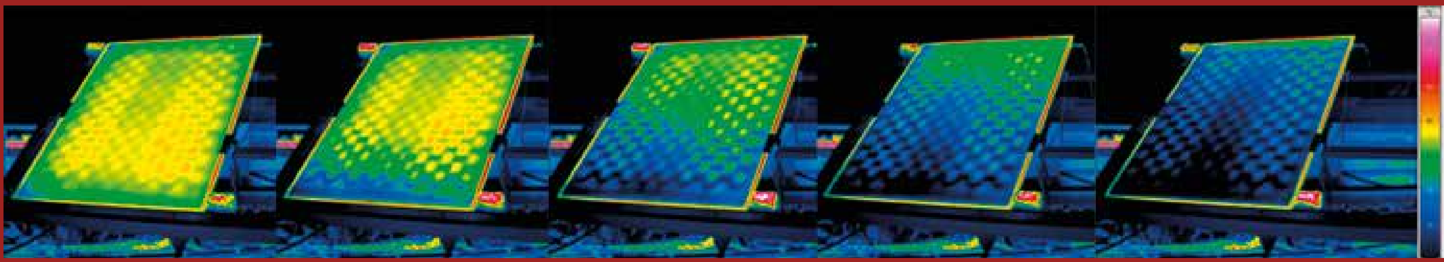
In the investigated embossing and stretch-forming process, the channel structure is initially created in a metal plate with a knuckle joint press and a progressive die. Subsequently, a formed half-shell is welded together with a flat plate or a second half-shell and equipped with connectors. The influence of different absorbers on the thermal efficiency of the collector in the same collector casing can be described with the collector efficiency factor F′. We have calculated F′ for steel absorbers of different sheet thickness and numbers of channels per absorber width (Fig. 2). The gap between channels should be as narrow as possible. In the usual plate-and-piping construction, a narrow gap between channels implies additional piping and connections to the header pipe, and thus additional costs. If sheet-forming technology is applied, additional channels can be introduced almost without extra cost. For the collector to achieve high thermal efficiency, the absorber must also have a spectrally selective coating. We tested whether previously coated material can be used in the sheet-forming process. Our measurements of commercially coated samples did not reveal any change in the absorptance due to the forming process. However, the emissivity increased and thus suffered a change for the worse. The first coating experiments on steel substrates with our own sputtering equipment resulted in lower emissivity values. We achieved the best results on powder-coated steel substrates. Both the absorptance and the emissivity were comparable to those of commercial PVD (physical vapour deposition) coatings.

The project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

1 *Detailed view showing the header channel and the channel harp of a steel absorber. The 2 m² demonstration absorber was developed together with our project partner and measured at Fraunhofer ISE.*



2 *Calculated collector efficiency F′ (left-hand axis) as a function of the metal sheet thickness for 10, 20, 30 and 40 channels over 950 mm absorber width with the Material DC01 steel (left-hand axis). The heat loss coefficient UL = 3.5 Wm^{-2}K^{-4} was assumed.*



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CERTIFICATION OF PVT COLLECTORS

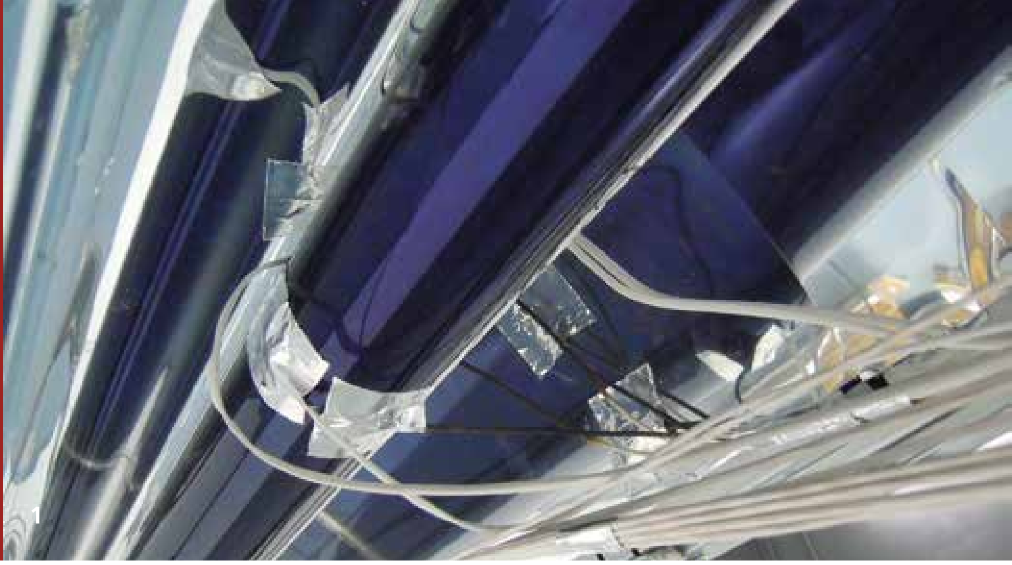
Photovoltaic-thermal hybrid collectors (PVT collectors) are currently the subject of numerous projects. By contrast, the market share is still small. As the number of manufacturers who offer PVT collectors is growing, a demand for standardized methods to characterize such products has arisen. Legal questions about introducing this type of product to the European market were also raised. The goal of the certification project was to increase transparency concerning technical properties, to support fair competition and to overcome barriers to market penetration. A market survey was prepared, five different products were investigated empirically and a system simulation model was set up.

Sven Fahr, Henning Helmers, **Korbinian Kramer**, Georg Mülhöfer, Christoph Thoma, Werner Platzer

When PVT collectors are introduced to the European market, it is important that electrical properties be declared in accordance with the Low-Voltage Directive (on the basis of IEC 61730 / 61215) as well as the Construction Products Directive, in the near future. In addition, many manufacturers also aim to have their products labelled with the Solar Keymark Label. This in turn requires complete testing according to the relevant standard, EN ISO 9806. In the context of applying these standards, considerable leeway for interpretation and unresolved questions were found which endangered the transparency and fairness of the evaluation methods. Together with our project partners (TÜV Rheinland Energie und Umwelt GmbH, FH Düsseldorf, Solarzentrum Allgäu GmbH & Co. KG), TestLab Solar Thermal Systems at Fraunhofer ISE initiated a project in consultation with TestLab PV Modules to work on the basic principles to resolve the questions. Within the project, a market survey was conducted on the products which are currently actually on the market (23 manufacturers). A total of five products were selected and subjected to a test matrix of empirical investigations, so that in combination with the tests carried out at TÜV, an optimal set of knowledge was gained for applying the tests. In addition, system simulation models were set up, and limiting situations were simulated on the basis of parameters which had been identified in the tests. An important result of the project is a pre-normative document which clarifies the most important questions concerning the application of existing tests to PVT collectors. The information contained in this document and the final report of the project make a significant contribution to ensuring fair competition and clearly regulated access to the market.

1 *Thermograph of a PVT collector during a rapid internal temperature change, an "internal shock", performed according to EN ISO 9806. The test simulates the stress situation during the hot start of a system. The test must be passed without any faults for the collector to be awarded e. g. the Solar Keymark Certificate. Electroluminescence is also used to analyze the results.*

The project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).



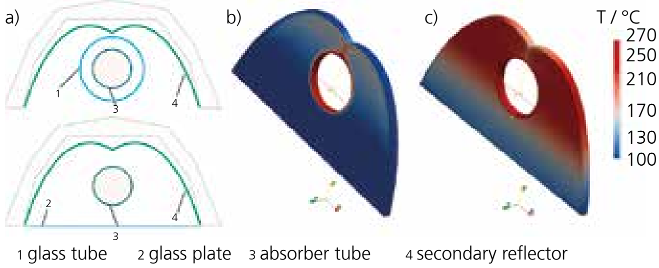
HEAT LOSS ASSESSMENT OF RECEIVERS IN LINEAR FRESNEL COLLECTORS

Heat loss characterization of linear Fresnel collectors is of significance for system design, annual yield estimation and implementation of control strategies. Besides the heat loss, also the temperature distribution along the components and temperatures reached by materials is highly relevant, particularly for the selection of materials and durability considerations. Fraunhofer ISE studies the thermal behaviour of the receivers in linear Fresnel collectors by laboratory tests and computational models, enabling us to support industrial partners from the technological design process up to the implementation and operation of a solar plant.

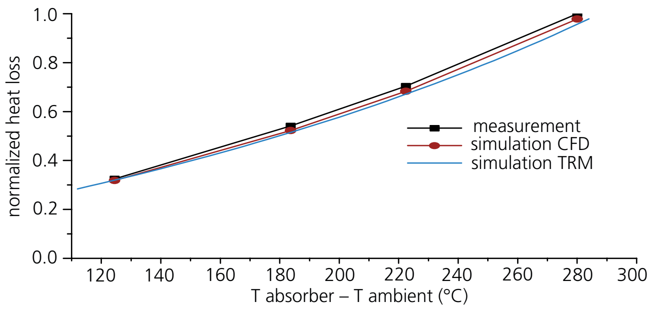
Felipe Cuevas, Anna Heimsath, Annie Hofer, Peter Nitz, Werner Platzer

Linear Fresnel collectors (LFC) present a potential technology for cost-efficient process heat and electricity. Their design requires a specific receiver unit, in which the heat loss varies with operational conditions. In our laboratory test, we emulate conditions in the field by means of electric heaters. In thermal steady-state conditions, the consumption of electricity is equivalent to the heat loss. Radiation incident on the secondary reflector increases its temperature, influencing the heat balance within the receiver. To account for this, additional heaters are installed above the secondary reflector to set temperature profiles. Simulations allow variation of parameters which cannot be varied in the laboratory due to technical constraints or high cost / effort. These include variable ambient conditions, receiver geometry and materials used. The measurements are used to validate the simulations. To model the thermal balance, we use Computational Fluid Dynamics (CFD) software and we have developed a simplified thermal resistance model (TRM). The main differences between the two models are computational time and the level of detail. CFD simulation is very time-consuming but can deliver detailed spatially resolved results (Fig. 2). Our TRM allows parameters to be varied easily, rapidly generating solutions and suitable to be integrated into optimization or sensitivity analysis routines. The results of our detailed heat loss assessment for LFC receivers provide better understanding and are included in parameter identification and performance tests of entire collectors.

1 *Temperature sensors on the absorber tube in an experimental set-up for thermal testing of an LFC receiver.*



2 *a) LFC receiver configurations. The glass tube may be evacuated. b) and c) Temperature distribution inside an LFC receiver as obtained by CFD simulation.*



3 *Comparison of results from heat loss measurements to those from simulation, showing good agreement.*

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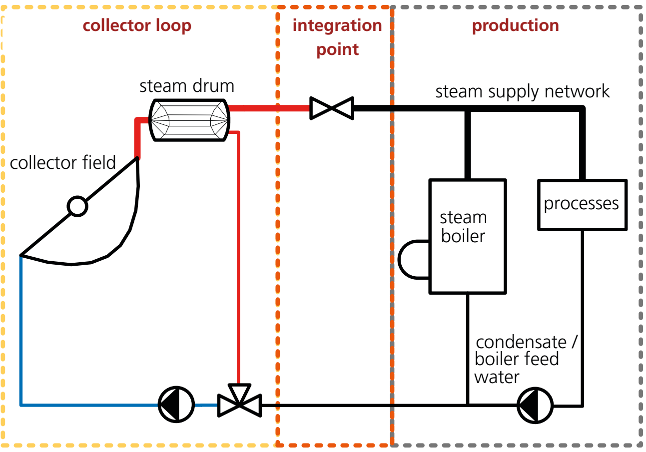
SOLAR PROCESS HEAT FOR INDUSTRIAL STEAM NETWORKS IN TUNISIA

Steam networks are often used to supply heat for industrial processes. Focussing solar thermal collectors can generate steam directly and feed it into these networks. This has the advantage that changes to individual processes hardly have any effect on the solar system. On commission to the GIZ Tunisia (Deutsche Gesellschaft für internationale Zusammenarbeit), we are working within the "DASTII" project (Diffusion des Applications Solaires Thermiques Innovantes dans l'Industrie Tunisienne) to disseminate solar thermal systems within Tunisian industry. We have written feasibility studies on solar process heat systems, with which emissions of 250 t of CO_2 should be saved annually. In addition, we are preparing a monitoring concept and lead local training sessions.

Annabell Helmke, Stefan Heß, Anton Neuhäuser, Werner Platzer



2 *Direct solar steam generation with a focussing collector. The feed water circulates continuously through the collector. If the temperature and pressure of the steam network have been reached, two-phase flow becomes established in the absorber tube. In the steam drum, the steam phase is separated out and subsequently fed into the steam network via a valve parallel to the boiler.*

1 *Linear concentrating Fresnel collector.*

In the "DASTII" project, we have developed a methodology to select suitable companies for solar process heat. We have applied it to investigate the technical and economic potential of solar steam generation for several production sites in Tunisia. The potential for increasing energy efficiency was also taken into account each time. We have represented the systems in our "ColSim" simulation platform and used it to model the steam profiles realistically. The goal of the study was to save 250 t of CO_2 annually in Tunisian companies by the use of solar process heat. Depending on the efficiency value of the replaced fuels and boilers, this corresponds to a quantity of heat ranging between 800 and 1100 MWh/a. The results show that a levellized cost of heat generation of five to seven euro cents per kilowatt-hour can be achieved without subsidies in Tunisia with a Fresnel collector. Realistic system costs and company-internal financing of the system were assumed in calculating these results.

Based on the results of our feasibility studies, companies will now be selected in which the solar systems supported by the GIZ should be installed. We will accompany the call for tenders and installation of the systems, supervise the monitoring process and evaluate the results over a period of two years. In parallel, we are conducting local training sessions for participants from ministries and research, and provide training resources for planners and technicians.

Our work in the "DASTII" project is also integrated into IEA-SHC Task 49 on "Solar Process Heat for Production and Advanced Applications".

http://task49.iea-shc.org

WATER PURIFICATION WITH SOLAR-POWERED MEMBRANE PROCESSES

Our expertise in the combination of solar energy and water purification technology is a unique feature of Fraunhofer ISE. We conduct research on dynamically operated reverse osmosis for seawater desalination with a direct PV power supply. Furthermore, we focus on membrane distillation as a membrane process which can efficiently use the temperature level supplied by solar thermal collectors or waste heat from power plant processes, geothermal plants or diesel generators. Most recently, we applied our expertise on ultrafiltration, reverse osmosis and membrane distillation in connection with solar energy supplies to a study for various island states.

Julian-Niclas Anhalt, David Düver, Joachim Koschikowski, **Joachim Went**, Daniel Winter, Werner Platzer

1 *PV-powered ultrafiltration system with integrated protection against microbiological contamination, installed in a trailer. Power supply: 2.2 kW$_p$ PV system and a battery system with 130 Ah capacity at 48 VDC; Filtrate production rate: 1.5–2 m³/h for pumping heights of up to 50 m (app. 20 m³/d).*

2 *Test stand for automated measurement of the liquid entry pressure for hydrophobic, porous membranes such as are used for membrane distillation.*

Applying ultrafiltration (UF), we envisage operation without any chemical purification of the water. Appropriate pre-treatment stages, intelligent operation management and purification procedures are being investigated. At present, we have combined a completely photovoltaically powered UF system with in situ chlorine production to protect the purified water from later microbiological contamination (Fig. 1).

In the reverse osmosis (RO) sector for desalination of seawater and brackish water, we are working on implementing dynamic operation management, in which the power drawn by the RO process is optimally adapted to the power available from the photovoltaic power supply. To keep the whole concept as simple and robust as possible, we have patented a pump type which we developed specifically for energy recovery, and implemented it for the first time this year. In 2014, we took a completely automated system into operation, in which a PV generator is emulated.

Concerning membrane distillation (MD), we offer the complete spectrum of development steps, from membrane characterization, system simulation, module construction up to complete solar-driven MD systems, and can apply this know-how throughout the world for targeted developments. MD separation processes for a great variety of industrial sectors are becoming increasingly important for our development tasks. This year, we took a laboratory test stand (Fig. 2) into operation, which allows MD membranes for different materials systems to be characterized in detail.

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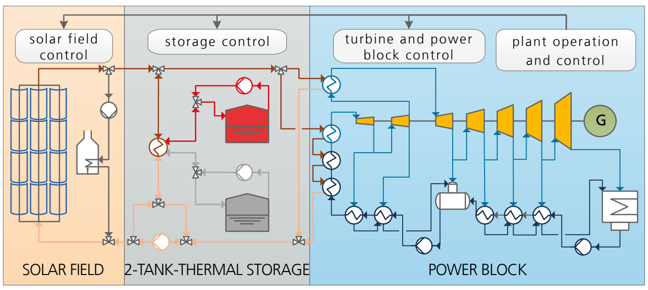
OPTIMIZING THE OPERATION MANAGEMENT OF SOLAR THERMAL POWER PLANTS

Reliable simulation models are essential for the development, design and optimization of solar thermal power plant concepts and the corresponding components, as well as to investigate operating strategies for the solar field, power block and storage integration. These elements are combined in the "ColSim-CSP" simulation environment at Fraunhofer ISE. Models for collectors, storage units and thermal desalination units are continually being extended and validated. The large number of available component models and the integrated materials data base make "ColSim-CSP" a powerful, flexible tool, both for rapid annual simulations and for detailed investigations with high temporal resolution, e. g. of the daily profile to simulate transients or the operating behaviour of solar thermal power plants.

Raymond Branke, Tom Fluri, Annie Hofer, Anton Neuhäuser, Bernhard Seubert, Alexander Vogel, Verena Zipf, Werner Platzer



2 *Schematic diagram of the ANDASOL 3 parabolic trough power plant, showing the level of detail applied in the "ColSim-CSP" simulation environment. The represented power plant components and the higher-level control algorithms each correspond to independent mathematical-physical models in "ColSim-CSP".*

1 *The ANDASOL 3 parabolic trough power plant in Guadix, Spain. The molten salt storage unit is at the front left of the photo, with the power block behind it and the solar field to the right.*

The object-oriented "ColSim" simulation platform is used as a tool to design and analyze control technology questions concerning solar energy systems and is continually being further developed. We thus have a very powerful, modular simulation environment available, which is used to answer questions related to research and development in various fields of solar thermal and other energy-technological applications.

The most comprehensive extension of the simulation platform in recent years concerned concentrating solar thermal energy conversion, in the "ColSim-CSP" development segment. It contains diverse validated component and system models as well as a materials data base to simulate CSP power plants (Concentrating Solar Thermal Power) with different types of collector technology. Thermal storage units, systems to provide process heat or cooling and thermal desalination systems can be integrated as required. At present, the component library of "ColSim-CSP" is being validated with real operating data from a parabolic trough power plant (Fig. 2), in order to refine the existing models for controlling the power plant and identify optimization potential in the operation management of this and comparable solar thermal power plants. The combination with cost models for techno-economic optimization requires close cooperation with clients. Usually, Fraunhofer ISE is responsible for carrying out the simulations and optimization and evaluating them. However, there is also the option of deriving client-specific simulation tools, which are then installed on the client's computer and can be run by the client.

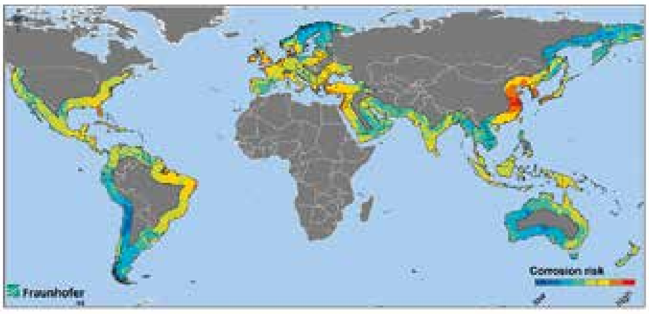
CORROSION AS A STRESS FACTOR FOR MATERIALS AND COLLECTORS

Atmospheric corrosivity is one of the most important stress factors for solar collectors. This affects absorbers and reflectors particularly strongly. For this reason, knowledge about the corrosive aggressivity of the atmosphere is essential for the development of new, innovative components for solar collectors. By measuring and mapping atmospheric corrosivity, we have gained important insights into the classification of regional climates. These serve as the basis for developing testing procedures for accelerated aging tests that are realistic with respect to the corrosivity and salt content of the atmosphere, and for specifying optimal anti-corrosion measures for solar collectors.

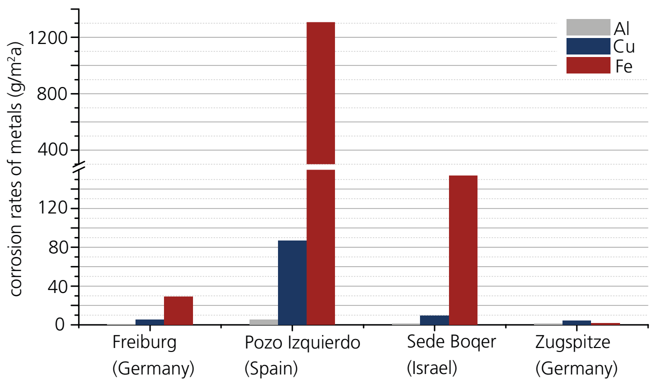
Elisabeth Klimm, Michael Köhl, **Karolina Slamova**,
Karl-Anders Weiß, Werner Platzer

The investigated climates are classified according to their corrosivity in four fundamental stress classes: rural, urban, industrial and maritime climates, whereby the last presents the greatest risk of corrosion. Due to varying local conditions (air humidity and precipitation) or specific air pollutants (particularly SO_2 and NO_x), significant differences in atmospheric corrosivity also exist within a single category. In order to obtain more accurate information about corrosive stress in the regions where solar thermal energy is applied, we are pursuing two different approaches. On the one hand, atmospheric corrosivity is being determined at 25 sites around the world (Fig. 3) by exposure of reference metal samples (Fig. 1) consisting of aluminium, carbon steel, zinc and copper. On the other hand, the corrosivity risk due to the atmosphere is being modelled and classified with the aid of the Geographic Information System (GIS – Fig. 2). Our goal is to support materials optimization for the various application areas in solar thermal collectors with our results.

1 *Exposure of metal reference samples to measure the atmospheric corrosivity at Fraunhofer ISE's outdoor test field on Gran Canaria.*



2 *Geographical distribution of the atmospheric corrosion risk on a world map.*



3 *Comparison of the mass loss due to corrosion for Al, Cu and Fe samples after being exposed for one year at four outdoor test sites belonging to Fraunhofer ISE.*

This work is part of the "SpeedColl" project and is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and participating industrial partners.

ENERGY EFFICIENT BUILDINGS

More than 40 % of the end energy demand in Germany is caused by the building sector. Similar statistics apply elsewhere in Europe and in most industrialized countries. The largest fraction of the energy is used to create indoor comfort and for domestic hot water and artificial lighting. The building sector thus has a major role to play in reaching the targets for climate protection.

Our work on energy efficient buildings encompasses all essential aspects of energy efficiency and the use of renewable energy in buildings – be it for residential or non-residential buildings, for new buildings or the existing building stock.

The development of holistic energy concepts for buildings, which take account of efficiency measures in the building envelope and optimized building plant technology, guarantees maximum indoor comfort accompanied by low costs and minimized usage of conventional energy sources. With our many years of experience and numerous powerful computer-based tools, we can support the development of energy concepts for buildings, commercial businesses and urban districts.

The building envelope is decisive for the energy demand of a building. Pioneering concepts for building façades offer more than just the classic functions of protection against wind and weather. Our work on façades, windows and lighting technology increasingly addresses the integration of active solar components – photovoltaic, solar thermal – into the façade as well as provision of further functions such as ventilation, heating or cooling. In addition, the combination of high visual comfort with the maximum possible utilization of daylight continues to play an important role.

Smart Home Technologies provide high transparency on building operation, energy consumption and operating costs. At the same time, they allow building operation to be influenced in a user-friendly way. Promising concepts also integrate options for cost-optimized building operation including renewable energy sources and energy storage, and can react to grid demands. We develop new hardware and software solutions and provide support on developing and implementing technology. Building operation management is an R&D focus in its own right. Our work here concentrates on the development of automated processes for the visualization and analysis of monitoring data, allowing errors in building operation to be detected early, savings potentials to be identified and the maintenance of building plant to be supported.

Ensuring high indoor comfort in combination with implementing the political goal of a climatically neutral building stock calls for powerful energy supply technology with low specific CO_2 emission, in addition to good thermal insulation of buildings. Electrically and thermally driven heat pumps play a prominent role in this respect. Our work in this area ranges from addressing fundamental questions on increasing efficiency and reducing costs up to accompanying market penetration measures with extensive field tests. Particularly the area of heat transfer offers considerable potential for cost saving and efficiency improvement, which is the rationale for developing heat transfer in building energy systems as a separately defined topic.

Processes for the cooling and air-conditioning of buildings play an important role in non-residential buildings – and also in residential buildings in warmer climatic zones. Our work is concentrating on highly efficient processes that take advantage of ambient heat sinks. We also develop novel, thermally driven dehumidification processes especially for humid climatic zones.

FURTHER INFORMATION

Staff	**125**
Full-time equivalent staff	**102**
Journal articles and contributions to books	**38**
Lectures and conference papers	**45**
Newly granted patents	**2**

www.ise.fraunhofer.de/en/publications/10

Outdoor test Facility for Real-size building Envelope Elements (OFREE) with an area of up to 4 m x 3.77 m (shown here without a façade element mounted). The black calorimeter absorber surface is clearly visible, as are the I-profile rails of the tracker, on which the rectangular calorimeter is mounted. The ventilation unit for a well-defined external heat transfer coefficient is installed after the façade element has been mounted.

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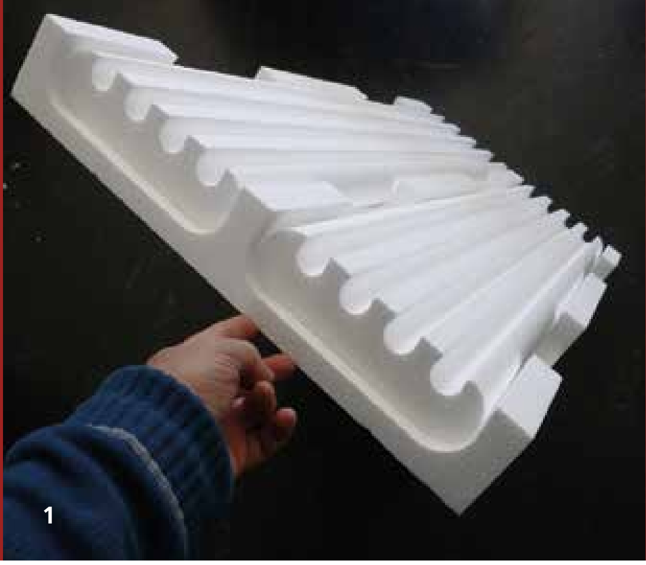


PRE-FABRICATED MULTIFUNCTIONAL FAÇADES

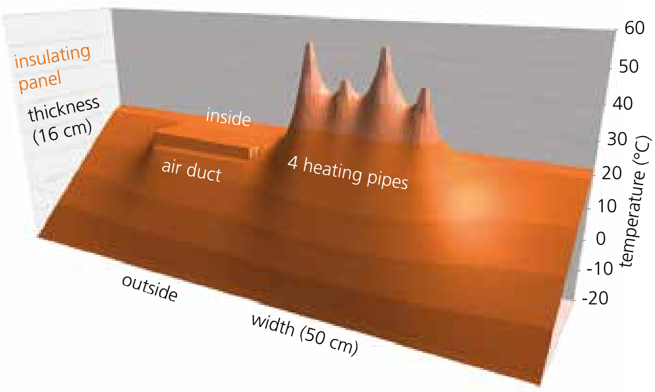
The German government plans to achieve a nearly climate-neutral building stock by 2050. Key elements to reach this goal are to significantly reduce the energy consumption of the building stock and to develop solutions to use renewable energy to meet heating loads. An interesting approach aims to combine façade insulation with HVAC systems. Several related projects are developing pre-fabricated insulating façade elements with integrated ventilation, heating and sanitation systems. These HVAC systems will be connected from the façade into the building by special window elements such that additional penetration of walls will not be needed.

Fabien Coydon, **Arnulf Dinkel**, Sebastian Herkel, Hans-Martin Henning

The specially developed insulating elements allow heating pipes, ventilation, electricity ITC and other systems to be integrated. These elements can be upgraded with additional functionalities during their service life. The existing HVAC systems in the building can be successively replaced by new systems without intrusion into the building structure or disturbing the inhabitants. This will allow a gradual transition to LowEx building systems within the existing building stock. To be attractive for the market, the systems will be highly standardized with a multitude of upgrade possibilities and individual choices for the separate systems. Each component, e. g. insulating panel, window, heating system or ventilation duct, can be mounted independently or in combination with traditional retrofitting systems and processes. This individual choice of modules combined with the upgradability means that solutions can be well adapted to clients' financial possibilities. In an initial development step, a variety of

1 *Polystyrene external wall insulation with integrated channels for ventilation ducts and heating pipes.*

2 *Ventilation configuration in the external insulation layer of an apartment block, pre-fabricated windows and insulation panels for the façade exterior insulation and finish system.*



3 *Temperature distribution in ventilation ducts and heating pipes within the external insulation layer.*

insulation systems with different geometrical configurations has been developed. First prototypes (Fig. 1) with integrated channels meet the specified requirements. Simulation (Fig. 3) of different constellations of façade-integrated ventilation ducts and heating pipes, combined with monitoring of an installed demonstrator, resulted in an optimized system design for insulation and ventilation with minimized energy losses. Within the "RetroKit" project, the developed approach will be transferred to apartment blocks in different climatic zones.

The "RetroKit" project is funded by the European Union.

www.retrokitproject.eu

1

EVACUATED INSULATING GLAZING UNITS: WINDOWS WITH VERY LOW U VALUES

Windows still represent a weak point in the thermal insulation of a building. For this reason, quadruple glazing is already being installed in Scandinavia. As the number of panes increases, so does the weight and the thickness (> 40 mm) of the windows. An alternative is presented by evacuated insulating glazing, consisting of a hermetically sealed unit of two glass panes separated by an evacuated gap. The thermally insulating properties of evacuated glazing systems are comparable to those of quadruple glazing ($U_g \leq 0.5\ Wm^{-2}K^{-1}$). The evacuated glazing was constructed with hermetic and flexible edge seals, uniting two areas of expertise at Fraunhofer ISE, the vacuum laser-welding process and coating of the individual components.

Samuel Beisel, Wolfgang Graf, Thomas Kroyer, Werner Platzer

1 *Prototype of an evacuated glazing unit with 0.5 mm spacers at 3 cm intervals. The spacers can hardly be seen. The total thickness of the glazing unit is 9 mm (the frame thickness is app. 20 mm) and its weight is comparable to that of a standard double-glazed unit. Windows with an area of 1 m x 1 m are currently being developed by Fraunhofer ISE.*

The goal of the "VIG-S" project is to develop processes for the production of evacuated insulating glazing units. All the necessary process steps have been investigated and optimized. The target U_g value of $0.5\ Wm^{-2}K^{-1}$ can only be achieved if a maximum pressure of $< 1 \times 10^{-3}$ mbar can be maintained. This demands a hermetic and flexible edge seal, which not only guarantees air tightness throughout the entire service life but also withstands movement due to thermal expansion of the glass panes. Implementing this edge seal presents the greatest challenge and is thus the main topic of this project. The edge seal is created by an adapted glass / metal bond. Glass and metal substrates are sputter-coated with a thin-film stack, on-to which soft solder is applied. Each pane of glass forms half of an evacuated glazing unit. Two panes are then transformed into a complete evacuated glazing unit by a laser-welding process in vacuum. In order to prevent mechanical contact between the two glass panes due to atmospheric pressure, spacers are introduced into the cavity before the laser-welding process. The size, form and distribution of the spacers are chosen such that they hardly have any visual impact on the finished product (Fig. 1).

The "VIG-S" project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

www.vig-info.de

OUTDOOR MEASUREMENT OF FULL-SIZE, ACTIVE FAÇADE ELEMENTS

Building-integrated solar systems (BISS) use the sun to meet some or all of a building's energy demand, minimizing the consumption of non-regenerative energy. For non-residential buildings with large façade areas, façade elements are pre-fabricated which can be e. g. 3.5 m high and 1.5 m wide. These elements are then successively mounted at the building site. Our new Outdoor test Facility for Real-size building Envelope Elements (OFREE) allows this type of façade element to be measured with regard both to the inward energy flux through the façade and to photovoltaic and solar thermal yields.

Ulrich Amann, Paolo Di Lauro, Sven Fahr, Johannes Hanek, Korbinian Kramer, Tilmann Kuhn, **Christoph Maurer**, Hans-Martin Henning

The new OFREE outdoor test stand can be used to measure façade elements with a height of up to 3.77 m and a width of 4 m, allowing original façade elements to be used. A further advantage of OFREE is that the test sample is exposed to natural sunlight. In the laboratory, quasi-homogeneous and quasi-parallel irradiation of a larger area is practically impossible. However, this is particularly important for angle-selective façade elements. Thus, properties can be measured for different incidence angles very accurately, without interference from divergent beams.

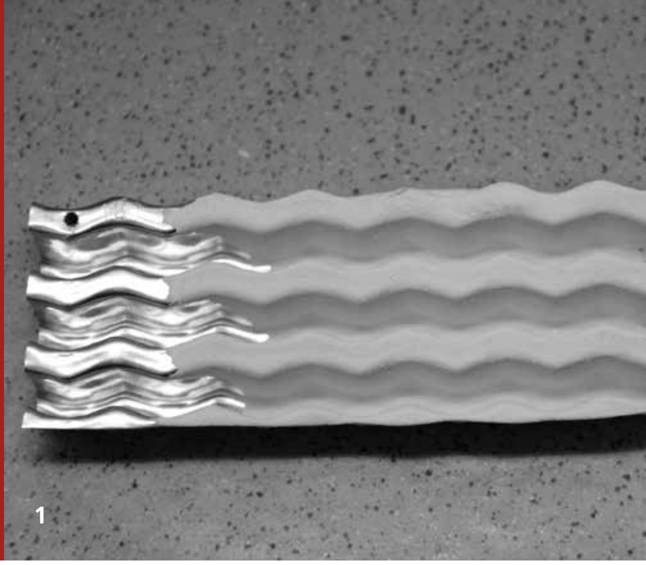
The new test stand is based on a solar tracker. It has been designed to be mechanically strong enough to support façade elements with a mass of up to 1.5 t. The tracker can be positioned at different angles with respect to the solar radiation, so that many different situations that can occur in reality can be reproduced. In addition to façade elements, roofing elements can of course be measured. A calorimeter is mounted on the tracker. This replaces the interior room and can be set precisely to a temperature between 15 °C and 70 °C. The calorimeter has a black surface to absorb the solar radiation transmitted by the façade element as completely as possible. In addition, heat-flux plates are integrated into the calorimeter to measure the energy flux from the façade to the calorimeter. This allows the energy fluxes on complex, multi-functional façades to be balanced under realistic conditions. A photo of the test stand can be seen in Fig. 1.

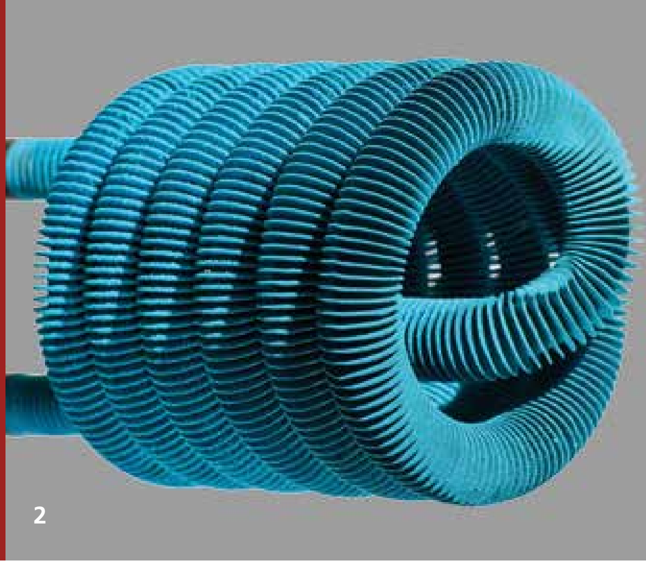
1 Outdoor test Facility for Real-size building Envelope Elements (OFREE) without a façade element mounted. The black calorimeter absorber surface is clearly visible, as are the I-profile rails of the tracker, on which the rectangular calorimeter is mounted. The ventilation unit for a well-defined external heat transfer coefficient is installed after the façade element has been mounted.

The OFREE test stand can be used to characterize building-integrated photovoltaic (BIPV), solar thermal (BIST) and photovoltaic thermal (BIPVT) modules, as well as passive façade elements, transparent or opaque. In addition to quasi-stationary determination of the g value (total solar energy transmittance; solar heat gain coefficient – SHGC), dynamic measurements can be used to validate detailed physical models, with which the façade performance can be simulated for other locations, installation conditions and applications.

The project was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

www.ise.fraunhofer.de/en/service-units/testlab-solar-facades





SORPTION MATERIALS AND COATINGS FOR ADSORPTION PROCESSES

Adsorption processes on porous materials form the central element in numerous technical processes. These include gas storage and separation, heterogeneous catalysis and particularly processes within thermally driven heat pumps and chillers. Our research is focussing on the application of a new class of materials, metal organic frameworks (MOF), to these heat conversion processes for resource-efficient generation of heat and cooling energy. We have succeeded in synthesizing various water-stable MOF compounds and developing two complementary coating processes, with which the MOFs can be applied to heat exchanger structures. Our work has already reached a pre-industrial stage.

Phillip Bendix, Dominik Fröhlich, **Stefan Henninger**, Felix Jeremias, Harry Kummer, Gunther Munz, Peter Schossig, Hans-Martin Henning

At present, silica gels or zeolites are used in adsorption heat pumps. Novel, crystalline compounds of the metal organic framework (MOF) class are based on a unique chemical building-block system and combine chemical variability with interior surface areas which can be enormous (SBET > 4000 m^2/g). Unfortunately, most representatives of this class are quite unstable in water vapour.

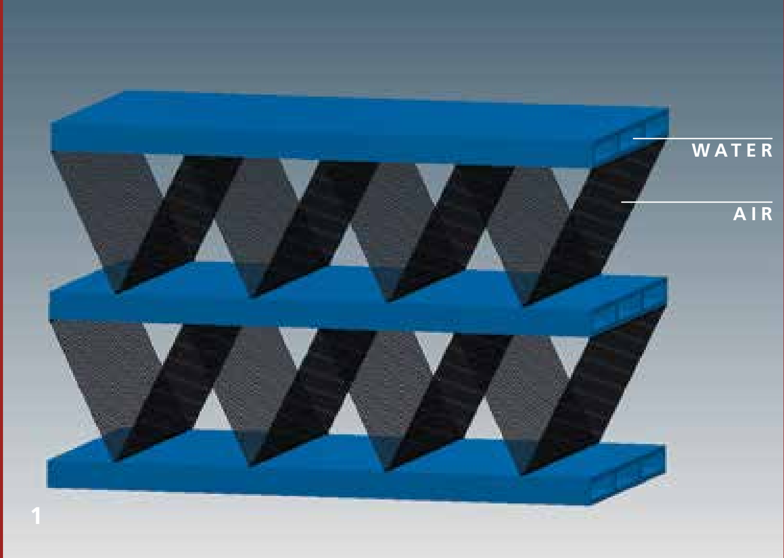
Over the last few years, we have been able to identify and synthesize promising compounds which feature a high water vapour capacity (up to 1.4 g/g) as well as long-term stability (more than 5000 adsorption cycles). At the same time, we were able to upscale the synthesized quantity.

With these new, high-performance adsorbents, the demands on heat and mass transport are also raised simultaneously. Particularly in cyclically operated applications such as adsorption heat pumps and chillers, it must be guaranteed that the cooling medium (e. g. water, alcohol) has easy access to the surfaces and that good thermal contact is made so that released heat can be removed quickly. We developed two complementary coating processes – one indirect, the other direct – which met these criteria and filed patent applications for them.

In the indirect coating process, the sorption material is deposited together with a binder onto the substrate structure. Here, flexibility with regard to the adsorption material and the substrate material is advantageous. This allows the adsorption material, the heat exchanger material and the respective geometrical configurations to be best adapted to the process specifications. We have already prepared coatings on different metals and ceramics. In addition, a broad palette of adsorbents such as silica gels, zeolites, silica alumino-phosphates (SAPO) or also MOFs can be used. In the direct crystallization process, the functional layer with a thickness of up to 200 µm is deposited directly onto the substrate surface from a solution of the MOF "building blocks". The thermal contact resistance between the coating and the substrate corresponds to that of a classic soldered connection. We were able to prove that the coating is optimally accessible and simultaneously features very high mechanical stability.

1 *Binder-based coatings of a three-dimensional substrate structure.*

2 *Finned copper heat exchanger tube that has been coated by the direct crystallization process. Such tubing is used e.g. in adsorption chillers.*



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EFFICIENT HEAT TRANSFER WITH METAL MESH STRUCTURES

Initial investigations of heat exchangers which use woven or knitted meshes of metal wire as the heat transfer structure have demonstrated a large potential for mass reduction and energy saving. In the "EffiMet" joint project, which is supported within the "KMU-Innovativ Programme" of the German Federal Ministry of Education and Research (BMBF), Fraunhofer ISE is cooperating with Visiotex GmbH, Hattler & Sohn GmbH and Fraunhofer IFAM in Dresden to investigate the theoretical background, identify technical implementation routes and implement the results with selected typical components. The results from one of the constructed components show that about 50 % of the material needed to increase the surface area can be saved for the same energy efficiency values. Correspondingly, the energy efficiency can be raised while keeping the amount of material used constant.

Hannes Fugmann, Eric Laurenz, Björn Nienborg, **Lena Schnabel**, Hans-Martin Henning

The large potential for saving material is caused by the heat transfer medium flowing around many individual, thin wires. Compared to surfaces made of thin sheet metal (fins), wires can provide twice the surface area for the same amount of material. Thus, if the fin thickness is equal to the wire diameter, half of the mass can be saved. In addition, when the heat transfer medium flows around the wires, the heat transfer coefficient is comparatively high, so that significantly more heat can be transferred for the same surface area.

The heat transfer is already relatively high for low flow rates, so that low pressure losses can be achieved. In order to achieve not only material savings but also high energyefficiency (transferred thermal power in relation to consumed pump or ventilator power), macroscopic layouts are needed which allow only low flow rates near the wire structures. In one such macroscopic layout, the heat transfer medium flows through the mesh in a macroscopic meander structure with a cross-sectional area which is much larger than the cross-sectional area of the heat exchanger front face. The design is currently being investigated in the "SolaRück" project. In this joint project, three industrial partners are developing heat rejection systems in the power range < 50 kW, which are well adapted to the requirements for solar thermal generation of cooling power. At Fraunhofer ISE, in addition to operation analysis, work is concentrating on investigating new heat exchanger designs which allow a significant increase in efficiency.

1 *Transformation from a design to a finished heat exchanger structure in the "EffiMet" project. A schematic draft design is shown on the left. On the right is a section of an air-water heat exchanger, where mesh-based fins have been soldered into the flat channels through which the water flows. The fins can be designed to have different densities. The wires and pipes were solder-coated by the Hattler company, the mesh was manufactured by Visiotex GmbH.*

The "EffiMet" project is supported by the German Federal Ministry of Education and Research (BMBF). The "SolaRück" project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

MEASUREMENT-BASED INVESTIGATION OF DIVERSE HEAT PUMP SOLUTIONS

Heat pumps present a very promising type of heating technology to implement the energy transformation in the building sector. There is great diversity among the technological variants and application areas that can be found in this sector. Depending on the building – residential, office, commercial or light industrial – and the boundary conditions and requirements, heat pumps can be used for space heating, for domestic hot water heating or also for cooling. Within the framework of several field tests, Fraunhofer ISE is determining the real performance of various technologies and applications, revealing potential for optimization and thus accompanying the dissemination and quality assurance of a key technology.

Constanze Bongs, Danny Günther, Doreen Kalz, **Marek Miara**, Hans-Martin Henning

The "WP Monitor Plus" project effectively continues the previous series of measurement campaigns to investigate the efficiency of electric heat pumps for space heating and domestic hot water in detached houses. Particularly efficient heat pumps coupled to the outdoor air or the ground, which are mostly installed in new buildings with low-temperature heating systems, were measured until the end of 2014. Best-practice solutions are being identified and possible contributions to energy saving in this application area demonstrated.

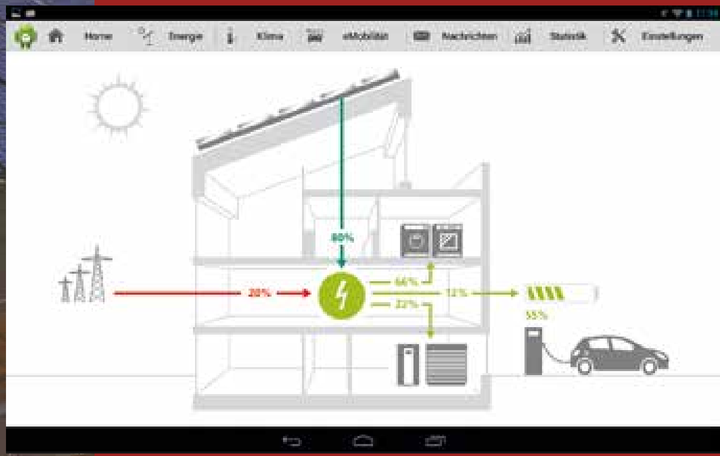
The first pilot systems with gas-fuelled absorption heat pumps are being investigated within the "Heat4U" project. The technology features high efficiency even with high inlet temperatures, and is thus intended to replace heating technology in existing residential buildings. The gas-fuelled heat pumps, which have a heating power of 18 kW (at 50 °C inlet temperature and 7 °C air temperature), are installed outdoors and use air as the heat source. Four field systems were installed in Poland, Great Britain, Germany and France and are currently being monitored. The field measurements are accompanied by laboratory measurements and system simulation. This project was supported by the European Union.

We are continuing to evaluate the energy, efficiency and operating performance in detail of 16 large heat pump systems in the power range from 40 to 322 kW_{therm} on the basis of measured data from field tests lasting several years. For the heat pump systems (heat pump with a compressor and a primary pump), seasonal performance factors were determined of 2.3 to 6.1 kWh_{therm}/kWh_{el} and 2.9 to 4.3 kWh_{therm}/kWh_{el}, for use of the ground and groundwater respectively as the heat source.

www.wp-monitor.ise.fraunhofer.de
www.heat4u.eu

1 *Gas-fuelled heat pump in the field test.*
2 *Examples of buildings with electrically powered heat pumps in the field test.*

1



2

POTENTIAL EXPLOITED – ELECTROMOBILITY IN THE ENERGY-PLUS HOUSE

The house of the future is ecologically friendly, energy-efficient and smart. Its smart energy control unit estimates the electricity generated by its own PV system and the household consumption for the next few hours and develops strategies e. g. to raise the share of internal electricity consumption. To achieve this, certain loads or storage units are operated flexibly, coordinated by the central energy control unit. Heat pump systems and electric vehicles, which do not always have to be completely charged immediately, are particularly well suited to this task. In the "Fellbach ZEROplus" project, this type of home energy management system is being developed and tested by residents in energy-plus houses in practice.

Robert Kohrs, **Marco Mittelsdorf**, Dominik Noeren, Günther Ebert, Hans-Martin Henning

Plug in and start charging – what functions for a Smartphone is not adequate for intelligent charging of electric vehicles. In order to calculate an optimal charging schedule, the system must know the current battery state of charge and the planned distance and departure time for the next trip. The energy management system uses this information together with weather forecasts and consumption predictions from historical data to estimate the energy flows in the house, and can thus generate an optimal charging schedule. This system was implemented within the "OpenMUC" software framework which was developed at Fraunhofer ISE (www.openmuc.org). The modular concept allows flexible adaptation for different applications. It supports a large number of communications protocols and contains an integrated monitoring unit, which simplifies the development of

1 *Charging the electric vehicle with PV electricity generated on site.*

2 *The graphical user interface visualizes energy flows within the house and provides information on the actual state of charge of the electric vehicle.*

customized solutions for the Smart Grid and Smart Homes. In the project, "OpenMUC" connects electricity meters, vehicle chargers, heat pumps and user interfaces with each other.

At present, the driver of an electric vehicle has to take account of its driving range and planned power consumption. Acceptance of intelligent charging is partly achieved by its usefulness: the system saves money and makes driving "greener". However, simple and convenient handling within everyday routines is the decisive point determining acceptance. The system developed at Fraunhofer ISE is thus equipped with an intuitive user interface and allows better understanding of the energy flows in the building.

The energy management system is currently being tested in a two-year field test in a group of energy-plus houses in Fellbach. Different optimization strategies are being tested and the practicability and user acceptance of the complete system are being investigated. In this way, the residents' requirements can be determined and the systems can be further developed, taking diverse criteria including user satisfaction into account.

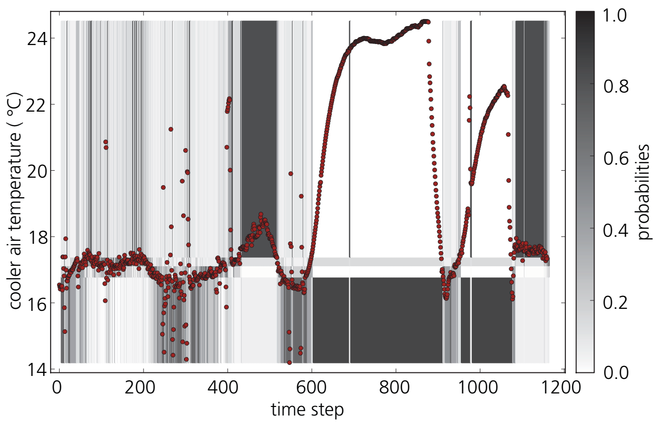
The project is supported by the German Federal Ministry for Transport and Digital Infrastructure (BMVI).

www.livinglab-bwe.de/projekt/fellbach-zeroplus

FAULT DETECTION AND DIAGNOSIS IN ENERGY-RELATED BUILDING OPERATION

There is a large potential for saving energy in building operation. Optimized building operation can lead to savings of 5 to 20 % in energy consumption. In practice, building performance is not supervised adequately because there is a lack of control systems which use the information contained in the data from building management systems. Within the "ModQS" and "CASCADE" projects, Fraunhofer ISE has developed and tested model-based methods for automatic fault detection and diagnosis, which continually monitor the energy-relevant operation of systems and quickly identify faults and optimization potential.

Gesa Böhme, Marc Eisenbarth, Sebastian Herkel, Thorsten Müller, Felix Ohr, **Nicolas Réhault**, Tim Rist, Markus Saas, Sebastian Zehnle, Hans-Martin Henning



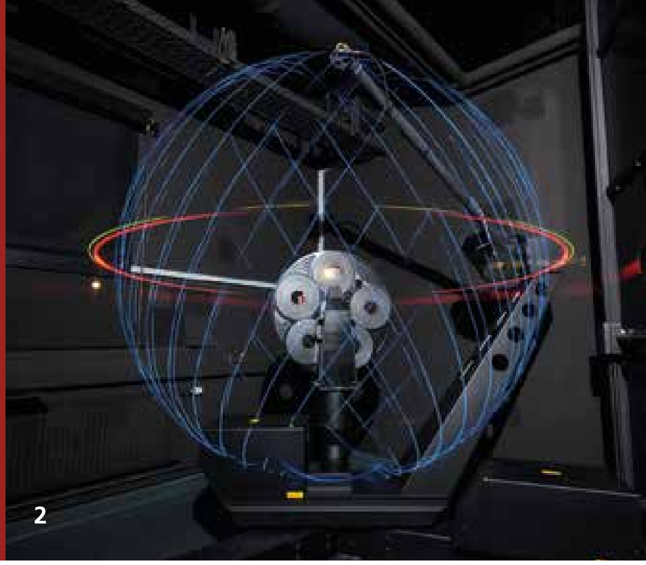
2 *Automatic fault detection in the cold water supply for an air-conditioning unit. The measured outlet air temperature (red) and the probability predicted by the qualitative model (grey shades) are shown. From time step 600 onward, the measured values are no longer within the range predicted by the qualitative model. A total annual energy-saving potential of up to 160 MWh was determined for this system.*

1 *Energy supply for an air-conditioning system in an airport building. Air-conditioning systems are major consumers of heat and electricity; their operation often conceals potential for energy saving. This can be recognized, identified and transmitted to the facility management by applying automatic fault detection and diagnosis methods.*

In real operation, buildings often consume more energy than is predicted by a demand calculation. This is largely caused by sub-optimal operation of the building technology plant and the existence of faulty system components and operating states. Common errors include e. g. defective sensors, incorrect schedules or inadequate control strategies. Despite the presence of modern building management systems in large buildings, there is often a lack of tools for continuous and automatic fault detection and diagnosis. We are developing algorithms for the next generation of building and energy management systems which can automatically recognize and diagnose faults in building technology plant such as heating, ventilation and air-conditioning systems. A new method based on qualitative models was successfully tested with measured data from a large air-conditioning system in an airport (Fig. 1). Qualitative models describe the behaviour of dynamic systems approximately and are able to predict future system states on the basis of probability values. If the occurrence probability of possible states for the rated system behaviour is known, operating states which deviate from optimal operation can be recognized. The advantage of this method is that only limited knowledge of the physical system behaviour is required and that implementation effort is minimized due to the qualitative treatment.

This work was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and the European Commission.

www.modqs.de **www.cascade-eu.org**



INTEGRATED SIMULATION OF COMPLEX FENESTRATION SYSTEMS

Windows and façades play a dominant role with respect to daylight, solar heat gains and thermal losses when the building energy balance is to be optimized. A major goal of the "Tageslichtverbundprojekt IV" (daylighting joint project IV) is to develop simulation programs for calculations that can be used to achieve lower energy costs and greater visual comfort in offices. Thanks to recent improvements in ray-tracing programs, it is now possible to calculate the light-scattering properties of complex fenestration systems. Based on a matrix representation of light transmission, the "Fener" simulation platform was developed, which allows daylighting and the energy balance due to fenestration systems to be evaluated. The program draws directly on detailed optical measurement data that are obtained with our pab-pgII photogoniometer. This combination will contribute to the technical development of new, innovative façade systems and also to their market integration.

Bruno Bueno, Johannes Hanek, Angelina Katsifaraki, Tilmann Kuhn, Jan Wienold, Helen Rose Wilson, Hans-Martin Henning

Complex fenestration systems (CFS) are systems which contain a light-scattering or a switchable layer. They include translucent thermal insulation materials and solar shading devices such as venetian and roller blinds. When complex fenestration systems are combined with suitable control functions, the thermal and visual comfort of indoor rooms can be significantly increased. At the same time, the energy demand for lighting, cooling and heating can be reduced.

As many novel façade materials are very complex, sophisticated measurement techniques are needed to characterize them. For this reason, Fraunhofer ISE has purchased a high-performance pab-pgII photogoniometer from the company pab advanced technologies Ltd. The photogoniometer can measure the scattered light distribution of passive materials as well as the angular distribution of small light sources. The angle-resolved transmittance and reflectance of the light can be saved as a bi-directional scattering distribution function (BSDF). BSDF data sets provide a complete description of the interaction between light and the sample material.

The "Fener" simulation platform was developed on the basis of a matrix representation for light transmission. It includes both exact and computer-efficient methods to simulate the thermal energy balance and daylighting in offices with complex fenestration systems. In addition, design alternatives can be compared quickly and cost-effectively with each other. The combination of the "Fener" program with the material characterization options offered by our new photogoniometer can support industrial partners in the development of new façade products and building planners in the selection of commercially available technology.

The work was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and internal Fraunhofer funding.

1 *Venetian blind system mounted on the KölnTriangle building.*

2 *pab-pgII photogoniometer at Fraunhofer ISE.*

STORAGE TECHNOLOGY

Many recent studies draw the conclusion that energy storage must play an essential role in the future energy system. It is thus necessary to develop efficient and cost-effective forms of energy storage. Furthermore, the complete energy supply chain must be taken into account and decisions should be made concerning the form for storing the energy, so that the final demand for electricity, heat, cooling energy or mechanical energy can be met optimally.

Fraunhofer ISE has been active for several decades in many diverse research areas concerning energy storage technology:

- electrochemical storage: battery technology ranging from lead-acid through lithium-ion to redox-flow
- chemical storage: storage systems based on methanol or hydrogen
- thermal storage: from cold storage through heat storage for buildings up to high-temperature storage for industrial processes and power plants

For electrochemical storage, we develop modules and system solutions with the necessary safety concepts and battery management systems for lead-acid batteries and diverse types of lithium-ion technology. These activities are supported by thermal, electrical and electrochemical modelling including aging, from the cell to the system level, as well as system simulation and life cycle cost analyzes. We develop intelligent charging and operation management strategies which can be easily integrated into microcontrollers for charge controllers, equipment controls and battery management systems. Further, we are optimizing the formatting process for lithium-ion batteries, a process which is important for performance and lifetime, but is also currently very cost-intensive. For redox-flow batteries, we are working on transferring new cell chemistry at the cell and stack level, the development of suitable methods to determine the state of charge and maintain capacity, and simulation-supported analysis and dimensioning of battery management systems.

Chemical energy storage can ideally complement electrochemical approaches for storage of renewably generated electricity. At the Institute, we are concentrating on electrochemical hydrogen generation by membrane electrolysis. Our work is currently focussing on lifetime analysis and the optimization of operation management for electrolyser cells and systems. Multiphysical modelling of the processes in an electrolyser cell is an important tool and supports the dimensioning of cell stacks and complete systems. We are presently setting up a new test centre to measure large cell stacks for PEM electrolysis with electric currents up to 4000 A and voltages up to 250 V.

The development of accelerated aging tests at the materials and component levels aims to provide information on the long-time stability of electrolysers more quickly.

In solar thermal technology, thermal storage serves to even out fluctuations in the solar yield. Meeting the demand for heating and cooling can then be largely decoupled from the prevailing solar radiation level. Water tanks are the main form of storage for temperatures up to 95 °C. We characterize, evaluate and optimize such storage units as individual components and within systems. The goal is to increase energy efficiency and reduce costs.

Particularly when only small temperature differences are available for thermal storage, latent heat storage offers much higher storage capacities than conventional storage of sensible heat. We develop and characterize phase change materials and storage systems for a temperature range from -30 °C to +600 °C. Simulations serve here to optimize the design of materials and storage systems. In particular, phase change storage promises high efficiency and compact equipment for storing cooling energy, a rapidly growing market.

The integration of high-temperature storage into solar thermal power plants makes it feasible to generate electricity when it is required. Molten salts are most commonly used as the storage medium. For this application, we develop, measure, evaluate and optimize storage concepts, which are designed for temperatures from 200 °C to 600 °C.

FURTHER INFORMATION

Staff	**49**
Full-time equivalent staff	**42**
Journal articles and contributions to books	**10**
Lectures and conference papers	**17**
Newly granted patents	**3**

www.ise.fraunhofer.de/en/publications/60

Interior view of the ServiceLab Batteries at Fraunhofer ISE. It is equipped with extensive testing facilities for cells, battery modules and complete systems of up to 1000 V and 0.25 MW.

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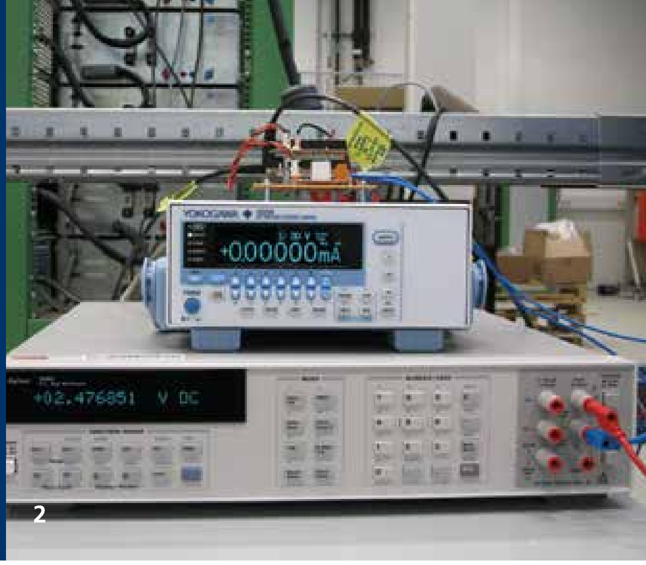


ACCELERATED FORMATION PROCESS FOR LITHIUM-ION CELLS

The battery market is increasingly dominated by lithium-ion (Li ion) cells for stationary and portable applications and the electromobility sector. To reduce the cost of this type of storage technology, production of these cells must become more cost-effective. An essential component of the production process is initial cycling of the battery through a well-defined charging-discharging sequence – so-called formation – and subsequent aging. This procedure takes a long time and is thus expensive. In the "Protrak" project, Fraunhofer ISE simulates the processes which occur during formation. Based on these results, new formation procedures are being developed, which are significantly faster and simultaneously improve the properties of the Li ion cells.

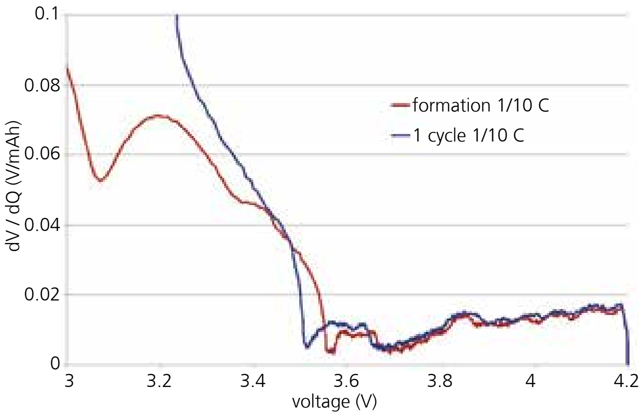
Maximilian Bruch, **Stephan Lux**, Lukas Rohr, Matthias Vetter, Günther Ebert

Common formation and storage processes from the industry and scientific research were investigated within the "Protrak" joint research project. Parameters relevant to the formation process were derived from the investigations. Together with Fraunhofer ISIT, possible modelling approaches were developed by Fraunhofer ISE as a basis for further work.

The test cells needed for model development were provided by Fraunhofer ISIT. Based on the model developed and experimental formation tests, optimized formation cycles were defined which enable the required calendar lifetime and cycling stability to be reached, as well as significantly reducing the time needed for this processing step. This work is fundamental to optimize processes also for cells based on other chemical reactions. Fraunhofer ISE filled the cells with electrolyte and carried out the formation sequences (Fig. 1).

1 Filling the lithium-ion cells with electrolyte in a glovebox before electric formation.

2 Test stand for highly accurate coulomb metering.



3 Derivative of the cell voltage with respect to charge versus cell voltage during a formation and a charging process for a lithium NMC (nickel manganese cobalt) cell. The difference between the first charging process (formation, red) and the second charging process (blue) is clearly evident.

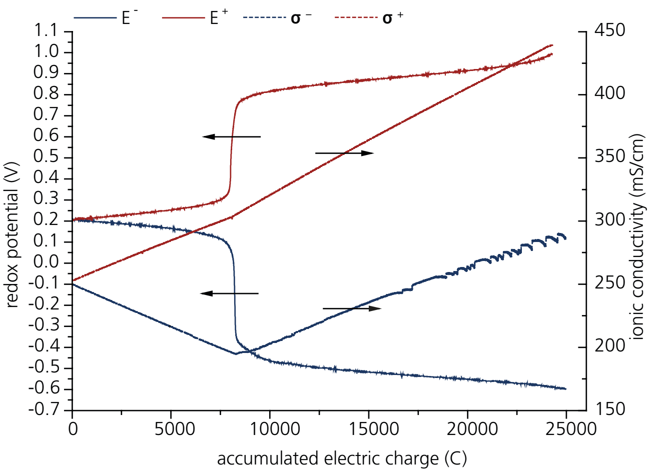
In addition, Fraunhofer ISE developed a test stand for highly accurate coulomb metering (Fig. 2). Different possible formation cycles are investigated there under well-defined conditions in large test matrices. In the cell production process, large numbers of cells must be temporarily stored under specified conditions for so-called aging tests. A process based on highly accurate coulomb counting and optimized formation cycles is currently being developed to significantly reduce the time and resources needed for these tests.

The project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

STATE-OF-CHARGE DETERMINATION FOR REDOX-FLOW BATTERIES

As part of the development work on scalable electric storage units, we are developing methods to determine the state of charge, in addition to addressing stacks, systems and battery management issues. Robust, simple and cost-effective determination of the state of charge is necessary for optimized operation management of redox-flow batteries. It must not only determine the instantaneous state of charge but also be used as a predictive tool to match generation and consumption. To this purpose, we are evaluating different measurement methods such as open circuit voltage, ionic conductivity and the redox potential of electrolytes at the single-cell level, and test these in technologically relevant dimensions with our fully automated stack test stands.

Kolja Bromberger, Malte Schlüter, Tom Smolinka, Matthias Vetter, Christopher Hebling



3 *Redox potential and ionic conductivity for both half-cells versus the accumulated electric charge during charging.*

1 *Cell stack with a 5 kW_{el} cell design during a long-term test in a test stand.*

2 *New test facility for cell stacks with an electric power rating up to 35 kW_{el}.*

Retaining capacity over long idle periods is essential for economic operation of a redox-flow system, in addition to high electrical efficiency and high cyclability. In order to use the available capacity of the electrolyte efficiently, it is crucial to determine the state of charge exactly. Unwanted side reactions in the electrolyte and transport processes across the separator negatively affect the state of charge during operation of a redox-flow battery and thus reduce the usable capacity. To determine and monitor the state of charge, we at Fraunhofer ISE are evaluating different measurement methods on single cells in a fully automated test stand with detailed measurement protocols. Suitable sensors are used to measure the open-circuit voltage across a reference cell, the ionic conductivity and the redox potential of the electrolytes. Fig. 3 shows the change in the redox potentials and the ionic conductivity of the anolyte and the catholyte during charging of a vanadium redox-flow battery. The measurement data are calibrated with a charge measurement and their reliability is tested in long-term tests on single cells.

The goal is to determine the state of charge accurately and then use this as a basis for developing optimal operation management strategies. It is particularly important that the method for determining the state of charge be suitable for prediction. Test stands for different power ranges from 1 to 2.5 kW_{el}, 2.5 to 10 kW_{el}, 4 x 5 kW_{el} and 35 kW_{el} are available to test the measurement methods and operation management strategies in technologically relevant dimensions.

SOLAR BATTERY SYSTEMS – SERVICE PROVIDERS FOR THE ELECTRICITY GRID?

Increasing numbers of electric storage units are being installed in buildings with photovoltaic systems to improve the match between fluctuating photovoltaic electricity generation and existing consumption profiles. However, PV electric storage units with purely local operation management criteria do not fully exploit their technical potential. Often free battery capacity is available which could provide system services for the electricity grid when required. The provision of primary control power in combination with a local increase in autonomy is particularly promising. The basic idea is to reserve some of the technically available storage capacity for different grid services, while the remainder serves to optimize local energy flows.

Georg Bopp, Thomas Erge, **Raphael Hollinger**, Günther Ebert

For the energy transformation to be successful, new actors and systems in the electricity system must not only supply power but also provide system services (e. g. control power reserves and reactive power supply) like conventional generators for the following reasons:

- to dispense completely with conventional generators during periods when enough electricity is generated from renewable sources

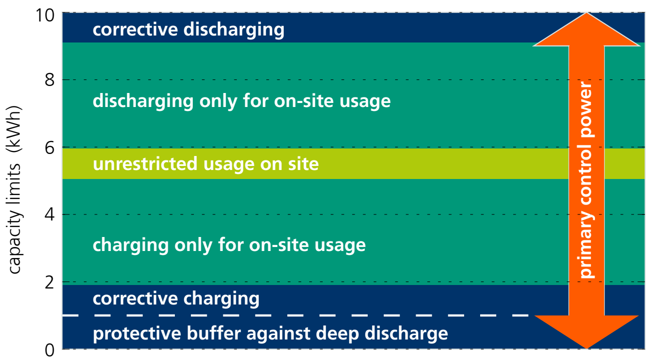
- to tap further sources of income for distributed and re-newable generators in addition to the supply of active power.

In the "Net-PV project", the combined power station approach, consisting of distributed PV battery systems with combined heat and power stations, is being developed and tested in a field experiment. The provision of primary control power in combination with locally increasing the degree of autonomy and reducing the grid load to the next higher grid level was identified as a particularly interesting option, both technically and economically.

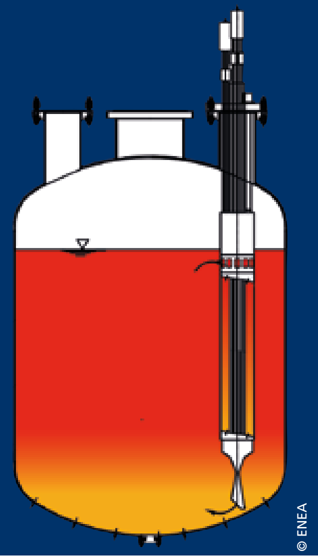
Simulations and investigations to date have shown clearly that PV storage units can provide additional benefits, both locally and for the grid generation and distribution system, which go far beyond their usual purpose today of increasing the consumption on site of locally generated PV electricity. This is desirable not only from a holistic system perspective but also shortens the amortisation periods for the relatively high investments in storage systems. Provision of the different services with the algorithms developed even proves to be symbiotic in nature.

The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

1 *Newly developed concepts are implemented and tested in the Smart Energy Laboratory at Fraunhofer ISE.*



2 *Usage of a battery, which provides primary control power independent of the state of charge (orange arrow), increases the autonomy of the local energy system depending on the state of charge (green zones) and is supported via the grid in emergencies by corrective charging (blue zones).*



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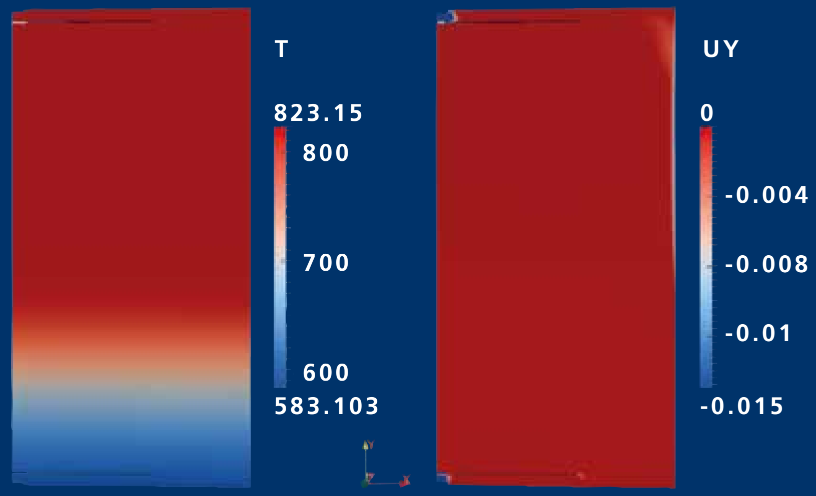
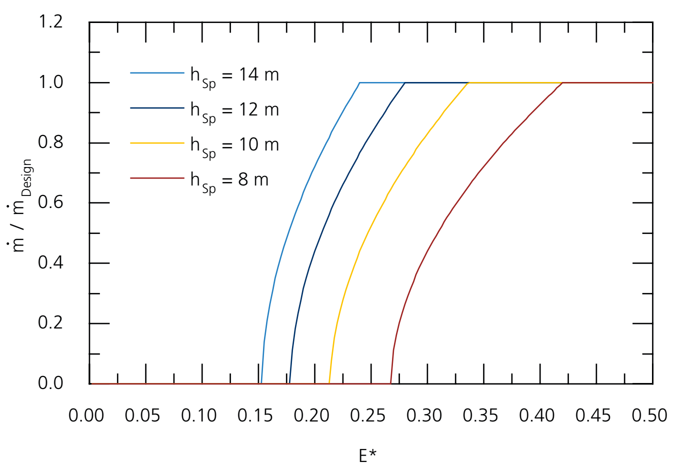


2

HIGH-TEMPERATURE STORAGE TANK WITH AN INTEGRATED STEAM GENERATOR

Thermal storage systems in solar thermal power plants make it feasible to generate electricity also when the sky is overcast or after sunset. This is a great advantage compared to wind energy or photovoltaic systems; it increases grid stability and supply reliability. Excess heat is stored in large tanks and used to operate the power generation cycle when required. To date, a molten salt storage unit with two tanks has been used in commercial systems. One approach to reduce costs is to store the hot and the cold salt in the same tank, separated only by the difference in density. In addition, this system allows the steam generator to be integrated directly within the storage tank, which brings further advantages.

Thomas Fluri, **Bernhard Seubert**, Werner Platzer



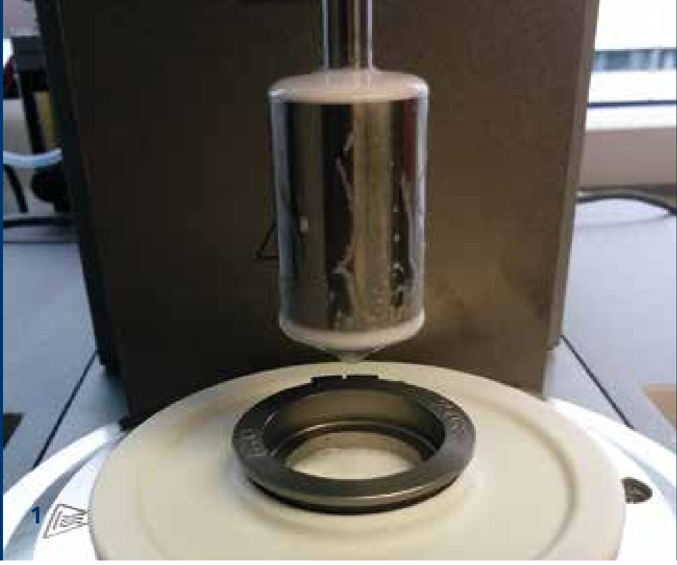
3 *Relative circulation rate through the steam generator versus the relative state of charge E* for different tank designs h_{Sp} and the same steam generator configuration.*

1 *Prototype system: Storage tank with an integrated steam generator and circulation of the storage medium through the steam generator activated by the density difference between the primary side and the storage tank.*

2 *Results of a tank charging simulation applying computational fluid dynamics (CFD); temperature distribution (left) and velocity profile (right).*

The project focussed on the modelling, analysis, optimization and practical implementation of the combined storage and steam generation unit. The system was treated at three different scales. A prototype (Fig. 1) was taken into operation at the beginning of the project and tested by the project partner, ENEA. The developed numerical models were validated with results from the prototype, and then used to design and dimension the system for pilot and commercial scales. In order to connect the pilot system with a storage capacity of 50 MWh_{th} to an existing solar thermal power plant, we prepared detailed dimensioning calculations and technical drawings. Commercial-scale design concepts were prepared and cost savings determined to enable comparison with other storage systems.

We were able to optimize the storage unit with respect to stratification behaviour, natural circulation and steam generation power. The best possible separation between the hot and cold storage media is essential for high efficiency of the complete system. We demonstrated with the help of simulations that the storage performance could be significantly improved by simple structural measures. In addition, the whole system was optimized with regard to a high circulation rate of the storage medium on the primary side of the steam generator. By changing the component configuration within the tank, the circulation rate can be increased many times under the same boundary conditions (Fig. 3).



PHASE CHANGE MATERIAL EMULSIONS FOR HEAT STORAGE

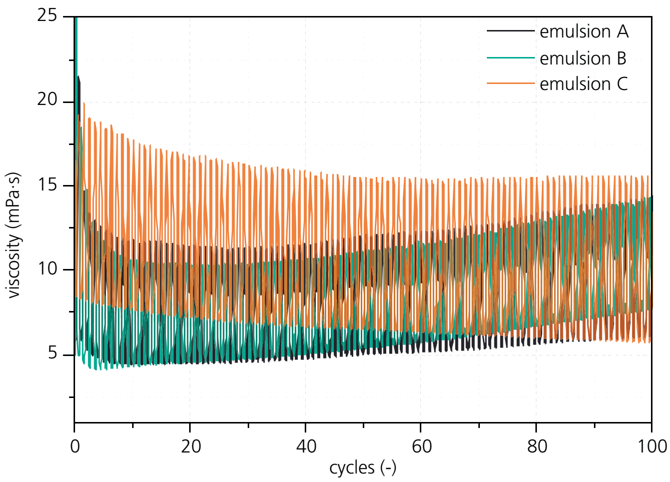
The heat storage density for small temperature differences can be increased four or five times compared to that of water by the use of PCM (phase change material) emulsions. This in turn implies that the storage volume can be four to five times smaller, so that mass and the space occupied can be saved. The heat storage and transport fluids are particularly well suited for cooling applications, but also for low-temperature heating systems in buildings and in the technical sector. They are produced by dispersing high-performance paraffins in water. A heat capacity of about 100 kJ/kg is reached for a paraffin concentration of 30 wt % and a temperature difference of about 6 K. The samples we have already prepared on laboratory and technical prototype scales are very stable to thermal and mechanical loads.

Stefan Gschwander, Lili Jia, Sophia Niedermaier,
Peter Schossig, Laura Vorbeck, Hans-Martin Henning

For these emulsions, oil is dispersed in water, with paraffins being used that are as pure as possible and feature high heat capacities. The phase change of the paraffin from solid to liquid and vice versa is used to store and release heat. For example, hexadecane and octadecane can store about 230 kJ/kg on phase transition. The stability of the emulsions is adjusted with tensides. When an emulsion is used as a heat transfer medium, the tensides must ensure not only that the emulsion remains stable when it is being stored, but also that it is stable throughout the phase change and when shearing forces are present, e. g. when the fluid is pumped.

The PCM emulsions prepared at Fraunhofer ISE with 30 wt % octadecane have a heat capacity of about 100 kJ/kg for a temperature difference of 6 K, meaning that they can store four times as much heat as water in this temperature range. During cycling tests in a rheometer, the prepared emulsions already demonstrate very high thermo-mechanical stability (Fig. 1, Fig. 2). Their application areas range from technical applications to the building sector. Their large heat capacity means that storage volumes can be appreciably smaller, which is particularly beneficial for mobile applications. In addition, very homogeneous temperature distributions can be achieved on cooling surfaces at comparatively low volume flow rates due to the almost isothermal heat storage process during the phase transition.

1 Stable PCM emulsions after thermo-mechanical cycling in a rheometer.



2 Thermo-mechanically stable PCM emulsions, which were subjected to a shearing rate of 100 1/s during 100 thermal cycles in a rheometer.

Our research was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

HYDROGEN AND FUEL CELL TECHNOLOGY

The expansion of renewable energy is characterized by an increasing share of fluctuating electricity generation from wind and solar energy. This creates new challenges for matching supply and demand for electricity in the grid. Hydrogen, which can be produced from water by electrolysis using electricity from renewable energy sources, is the only energy transfer medium which possesses the potential to store large amounts of energy also over long periods of time in a chemical form. Water electrolysers present an increasingly valuable control option for city utilities or grid operators to quickly adapt electricity generation to consumption and thus stabilize the grid frequency. Furthermore, sustainably produced hydrogen also forms a link to zero-emission mobility as a fuel for fuel cell vehicles, offering tank filling times and trip ranges which are comparable to those of conventional vehicles.

With our activities in the area of hydrogen and fuel cell technology, we offer research services concerning the generation, conversion and storage of hydrogen:

Our scientific and engineering research on electrochemical generation of hydrogen is concentrating on electrolysis of water in polymer-electrolyte membrane electrolysers (PEM). We carry out multiphysical simulation of cells and stacks. In addition, we construct functional working models – from the cell stack up to fully automated complete systems for pressurized operation up to 50 bar. Test stands for cell stacks up to 1 MW_{el} are available to us for the final stage of these developments. We prepare studies on the technology of water electrolysis and the usage of hydrogen within a solar energy economy.

Fuel cells convert hydrogen into electricity and heat with high efficiency. We develop fuel cell systems adapted to real outdoor conditions, especially for automotive technology, but also for decentralized stationary systems such as emergency power supplies and for portable electronic devices. Our research encompasses the construction, simulation and characterization of single cells, cell stacks and systems as well as the testing of peripheral and cell components under extreme climatic conditions and with respect to their electrochemical stability.

We have many years of experience in the chemical engineering and process technology of thermochemical hydrogen generation from fossil and biogenic fuels. These processes include reforming and pyrolysis. Beyond this, we have extended our work beyond energy-related applications to address chemical applications of biogenic fuels. We develop processes to synthesize liquid fuels, such as dimethyl ether or oxymethylene ether (DME or OME), or also chemical building blocks, which were previously derived from oil, out of hydrogen and carbon dioxide. In experimental investigations or studies, we assess the technological feasibility of new, energy-efficient and resource-conserving processes.

Our research spectrum on electrochemical and chemical engineering processes is facilitating the transition from fossil-fuelled applications to sustainable, zero-carbon energy technology.

Our research encompasses:
- stack development for PEM fuel cells and electrolysers
- multiphysical modelling of components, cells, stacks and complete systems
- electrochemical characterization of cells, cell stacks and systems
- feasibility studies of new chemical engineering processes, concentrating on heterogeneously catalysed chemical conversion
- measurement and controls technology for laboratory systems, prototype systems and functional models
- production technology
- technological, concept and user acceptance studies.

FURTHER INFORMATION

Staff	**76**
Full-time equivalent staff	**63**
Journal articles and contributions to books	**7**
Lectures and conference papers	**16**
Newly granted patents	**2**

www.ise.fraunhofer.de/en/publications/40

Detail of a mini-plant at Fraunhofer ISE to produce methanol and dimethyl ether (DME) from carbon dioxide and hydrogen.

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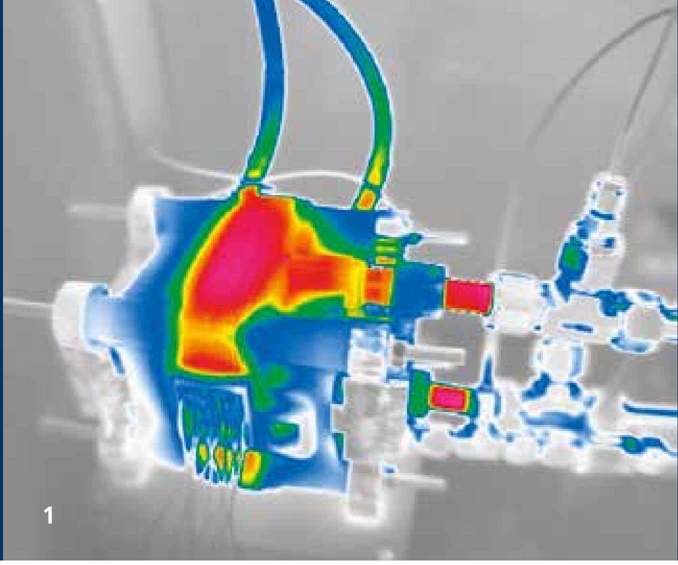


LONG-TERM STUDIES OF PEM PRESSURE ELECTROLYSERS FOR PTG APPLICATIONS

In the Power-to-Gas (PtG) concept, electricity from renewable sources is stored chemically as an energy-rich gas. In this joint project, carbon dioxide and hydrogen produced by electrolysis are converted into methane, which can be stored and transported in the natural gas network without difficulty. PEM (polymer electrolyte membrane) electrolysis is a particularly suitable process to produce the hydrogen: Usage of a membrane as a solid electrolyte results in high power density. Due to its excellent robustness to overloading and partial loading, PEM electrolysis can be operated very dynamically. The cell configuration enables operation at high pressure, so that there is no need for additional compressors for the methane production.

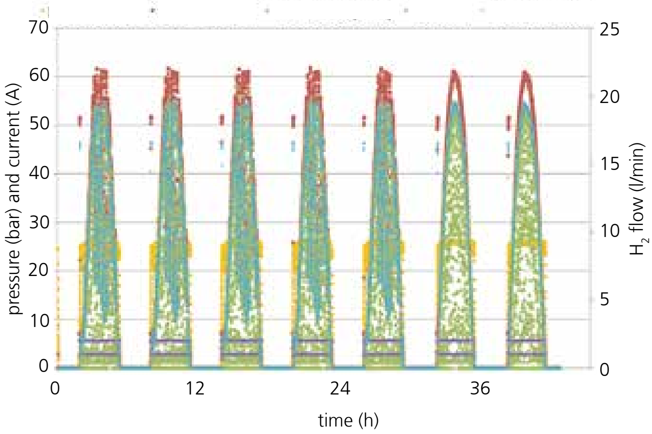
Peter Gesikiewicz, Beatrice Hacker, **Tom Smolinka**, Christopher Hebling

To understand the electrolysis sub-system better within the context of the complete Power-to-Gas system, we have set up a test facility with which different load profiles can be reproduced and long-term stability can be tested at the system level under realistic conditions. In addition, degradation behaviour under stationary conditions was tested over several thousand hours at the stack level.

To optimize the dynamic operation management, we have characterized a 6 kW PEM electrolysis system from our partner, H-TEC Systems, and analyzed individual components in detail. Energy balances were determined for the complete electrolyser at different load points and during externally applied, fluctuating power profiles. The results serve not only to detect losses but also to iteratively develop the hardware and operation management further in typical application cases. The experiments have demonstrated that the dynamic response of a PEM pressure electrolyser, coupled to either wind or PV electricity generation, completely fulfils the demands of PtG systems. Good efficiency values were obtained, which can still be optimized further in the lower partial load range. The utilization factors depended essentially on the ratio of the rated power of the electrolyser to that of the generator system. The gas quality of the hydrogen produced was excellent throughout the entire measurement period. Under the selected boundary conditions, up to 4700 full-load hours per year can be achieved with the simulated business model.

1 Thermographic image of a PEM pressure electrolysis stack. The stack was operated for several thousand hours in one of our fully automated test stands.

2 PEM pressure electrolysis system from H-TEC Systems in the test facility at Fraunhofer ISE.



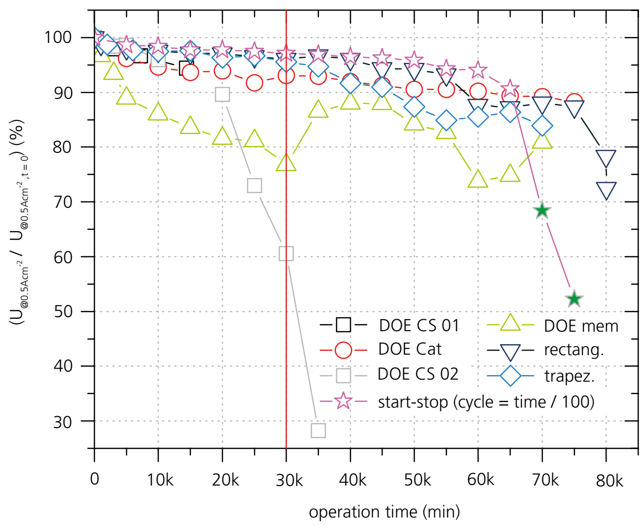
***3** Dynamic performance of the PEM electrolyser with an externally applied, fluctuating power profile corresponding to a typical PV generator during a week with changeable and sunny days.*

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

ACCELERATED AGING TESTS FOR PEM FUEL CELLS

The heart of a fuel cell is the membrane with its electrodes deposited onto both sides. The individual materials age at different rates during various stress situations in operation. We have analyzed the degradation of the components of a membrane-electrode assembly as a function of the electrochemical load in comprehensive long-term experiments. This allowed us to quantify the effect of stressors such as start-stop cycles, sudden changes in the electric load, idling cell voltage, humidity cycles, etc., on the lifetime of a fuel cell. This is the prerequisite for future online estimation of the life expectancy of a fuel cell, depending on its operating conditions.

Dietmar Gerteisen, **Ulf Groos**, Christian Sadeler, Mario Zedda, Christopher Hebling



2 *Reduction of the cell voltage due to various accelerated aging tests for up to 80,000 cycles.*

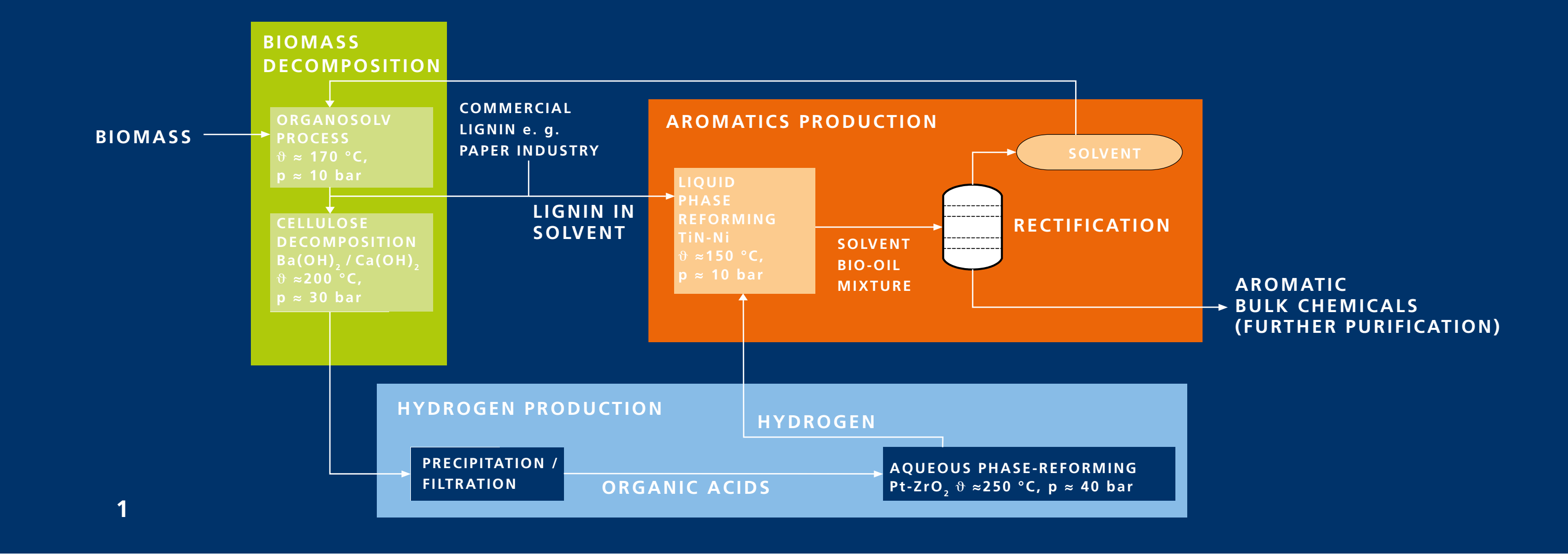
1 *Fuel cell laboratory for lifetime analysis.*

It is decisive to understand the degradation phenomena of a PEM fuel cell so that yet more stable materials can be developed and the fuel cell lifetime can be lengthened in future. In addition, this understanding is the basis for developing "state-of-health" models, which estimate the lifetime of a concrete system online. They could be used e. g. to alert the driver of a fuel-cell car to the need for maintenance.

To quantify the dependence of aging effects on operating events, we have adopted accelerated aging protocols from the scientific literature and applied them experimentally in long-term experiments of several thousand cycles. This allowed us to determine the time-dependent aging due to start-stop cycles, application of an idling cell voltage or different rapid changes in the load and relate these to the individual materials in a membrane-electrode assembly.

The main parameters used to indicate degradation, apart from voltage and current, included the electrochemically active surface area of the electrodes, the proton conductivity of the membrane, the diffusion barrier effect for reactants, the hydrogen diffusion rate through the membrane and the double-layer capacity of the cathode. They were determined by cyclovoltammetry, linear voltammetry and electrochemical impedance spectroscopy.

The work within the "LDP" and "STRESS" projects was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).



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DERIVING BASIC BUILDING BLOCKS FOR THE CHEMICAL INDUSTRY FROM BIOMASS

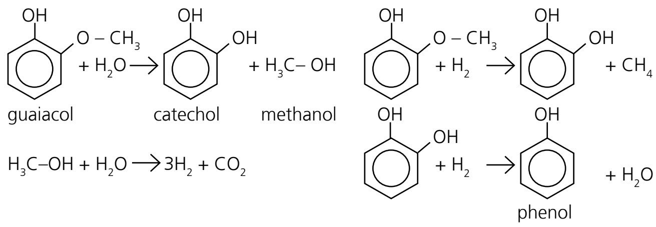
Whereas processes used today to decompose biomass primarily aim to extract individual products (e. g. cellulose) from the biomass, a large amount of the raw material, often lignin, remains as unused and contaminated residue. Our goal is to use the natural raw material as completely as possible. To do this, the conversion of lignin, a framework polymer based on aromatic hydrocarbons, is of central importance. In the "Dendrofining" project, this biopolymer is to be decomposed into smaller units by heterogeneous catalysis in the liquid phase, without destroying the individual components. Lignin monomers are valuable aromatic chemical building blocks, which are currently derived from petrochemical oil fractions in the chemical industry.

Thomas Aicher, **Malte Otromke**, Christopher Hebling

In a joint project between Fraunhofer and Max Planck, a novel, integrated complete process to gain aromatic basic chemicals from biomass is being developed and tested on a laboratory scale. The complete process is shown in a simplified form in Fig. 1. The biomass is separated into lignin and an aqueous phase with organic acids. The lignin is then dissolved in a simple alcohol and depolymerized with a novel catalyst by hydrogenolysis. The catalyst has been developed at the Max Planck Institute for Colloids and Interfaces. The hydrogen which is needed to decompose the lignin is gained from liquid phase reforming of the organic acids from the first process step.

To investigate the lignin depolymerization, initially experiments were carried out with lignin model compounds, e. g. guaiacol, where we achieved selective conversion to simpler aromatics. These reactions are important for the subsequent narrowing of the product spectrum. The influence of catalysts based on platinum and nickel on guaiacol as a model compound were investigated under hydrothermal conditions. We determined the conversion and reaction yields illustrated in Fig. 3. Kinetic parameters can be used to calculate the reaction profile such that retention times are chosen to result in a maximum yield of the desired product (e. g. phenol). The reaction rate and yield for the individual substances can be simply controlled by the addition of very small quantities of methanol (e. g. 1/3 molar with respect to guaiacol).

1 *Schematic process overview of an integrated bio-refinery to produce aromatic basic chemicals, consisting of biomass decomposition (green), hydrogen production (blue) and lignin depolymerization by hydrogenolysis (orange).*



2 *Simplified reaction network for guaiacol in water under hydrothermal conditions.*

Catalyst	Conversion Guaiacol	Yield Catechol	Phenol	Adsorbed Species
Pt/ZrO_2	0.96	0.47	0.28	0.25
Pt/ZrO_2 + MeOH	> 0.99	0.01	0.56	0.43
Pt/TiO_2	0.34	0.00	0.00	0.99
Pt/C	0.84	0.67	0.05	0.28
Ni/C	0.36	0.05	0.01	0.94

3 *Conversion and reaction yields for the hydrothermal reaction of guaiacol.*

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COMMUNAL ENERGY NETWORK – POWER-TO-GAS IN NORTH FREIBURG

Power-to-Gas as an energy storage form and a prerequisite or supportive measure for the energy transformation is currently being discussed intensively by scientific circles and society at large. However, in order to build corresponding systems on a larger scale than purely demonstration projects, their economic viability and integration into the relevant networks are crucial. In the "Kommunaler Energieverbund" project (communal energy network), experts in Power-to-Gas and energy management and networks from Fraunhofer ISE are cooperating with the University of Applied Sciences in Offenburg to develop operation management algorithms for Power-to-Gas systems that are integrated into electricity grids and gas networks. The goal is to achieve economic and energy-relevant viability of Power-to-Gas systems in the communal context.

Raphael Hollinger, **Christopher Voglstätter**, Christopher Hebling

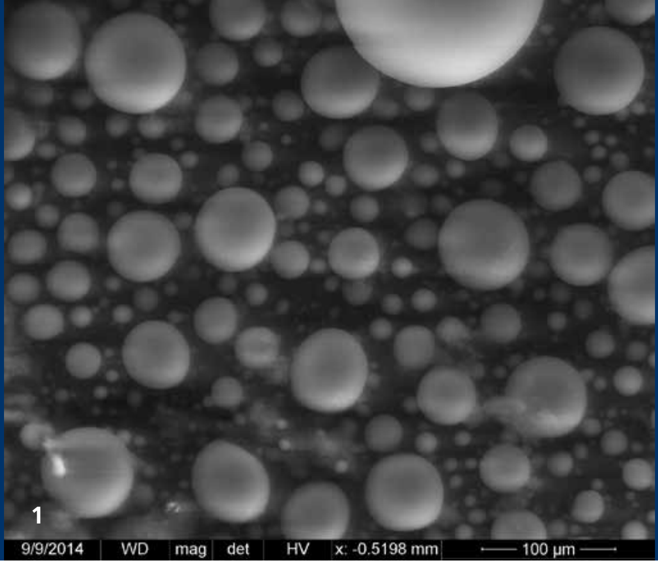
Within the "Kommunaler Energieverbund" project, a control algorithm is being prepared for the electrolysis system as a core component in a Power-to-Gas system. The algorithm will allow different business models for controlling such systems to be evaluated and lead to optimized operation of the systems. They are to be controlled under the boundary conditions applying to a communal energy network. In addition to the local electricity grids, heating and gas networks will be taken into account if appropriate. The algorithm will be developed and tested in a simulation framework that is to be created for this task and will allow different scenarios and boundary conditions to be investigated.

1 Gas pressure regulation plant in Offenburg, owned by the project partner and local distribution grid operator, badenova / bnnetze.

In addition, the construction of a Power-to-Gas demonstration system in North Freiburg will be examined as part of the project, and implemented if it is authorized. With it, feeding hydrogen into the communal distribution network could be demonstrated, the algorithms validated and project results checked.

In cooperation with the University of Applied Sciences in Offenburg, operating algorithms will be generated as components for a communal energy utility and an industrial enterprise, with their different boundary conditions and dimensions. Comparison of these results will provide further information on applying Power-to-Gas on a communal scale.

The project is supported with funds from the State of Baden-Württemberg and by the project agency established at the Karlsruhe Institute of Technology.



EXPERT NETWORK FOR FUEL CELL PRODUCTION TECHNOLOGY

In the dissemination of fuel cell technology, a classic "chicken and egg" problem can be observed at present. The manufacturers of production plants are refraining from investing because the fuel cell market is too small, while potential users are waiting for suitable production plants. In order to resolve this dilemma and create a base for more widespread usage of fuel cell technology, we have initiated an expert network to develop scalable production processes. In doing so, we draw on both the solidly based competence of our fuel cell experts and also our many years of experience in developing and optimizing production technology and fabrication concepts.

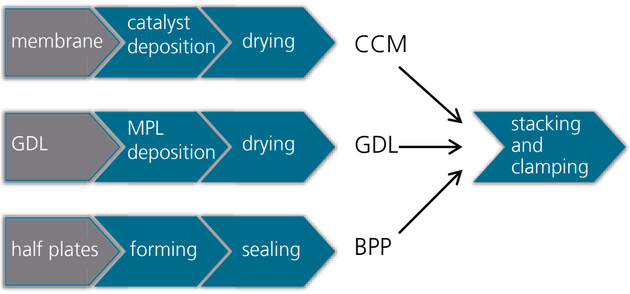
Robert Alink, Max Bergau, Daniel Biro, **Florian Clement**, Ulf Groos, Florian Pier, Benjamin Thaidigsmann, Ralf Preu, Christopher Hebling

High production costs and inadequate hydrogen infrastructure are still acting to prevent significant dissemination of fuel cell technology. The "H2Mobility" initiative is working to change the state of infrastructure in Germany. Fifty hydrogen filling stations are planned for 2015, primarily in urban areas. Already by 2023, 400 filling stations should ensure unlimited hydrogen mobility.

However, the production costs are also still too high. Here, we are cooperating with eight industrial partners within the "Technology Network for Fuel Cell Production Technology H2PRO" to improve the situation. Together, we are developing scalable production solutions for PEM fuel cells. The focus is on techno-economic evaluation of different production approaches. With the research results, suitable production technology can be selected and targeted investment can pave the road toward cost-effective fuel cell production. This in turn is the basis for more intensive usage of hydrogen as a fuel both for individual mobility and in utility vehicles.

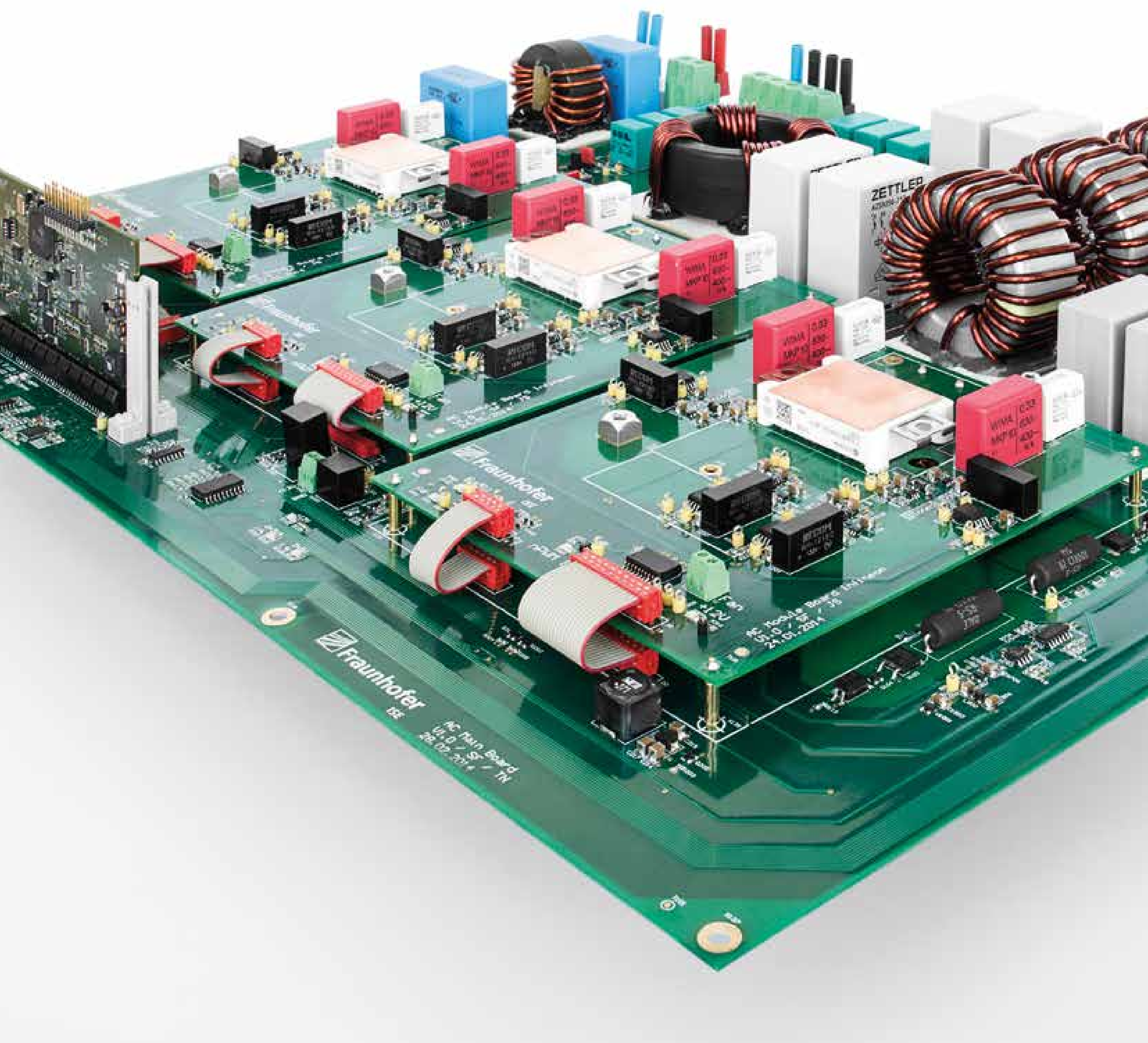
Work in the industrial network is flanked by internal development work on electrode coating and the creation of microporous layers on the carbon gas diffusion layer to ensure a homogeneous gas supply. We are using our coating and screen-printing equipment to this purpose and apply our extensive characterization options to measure the performance of material samples and test cells.

1 *ESEM image (ESEM: environmental scanning electron microscope) of a microporous layer (MPL) prepared at Fraunhofer ISE, which ensures a homogeneous supply of gas within the fuel cell. Water management is very important for cell function. The MPL is thus made hydrophobic by addition of PTFE. The water-repellent property is evident from the large contact angle of the water droplets in the image.*



2 *Simplified production scheme for manufacturing a PEM fuel cell stack. A single cell consists of a catalyst-coated membrane (CCM), a gas diffusion layer (GDL) and a bipolar plate (BPP).*

ENERGY EFFICIENT POWER ELECTRONICS



Power electronics is a key technology for the energy supply, drive technology and vehicle manufacturing sectors. In particular, it is fundamentally important for transformation of the national energy system. Due to continual further development of electronic components and improved circuit designs, many power electronic components and systems today are smaller, lighter, more efficient and less expensive, or completely new functionalities have been created.

Fraunhofer ISE develops power electronic components and systems for many application areas. Our primary focus is on inverters, converters and controls for use in power supply and transmission. Particular attention is paid to optimal integration into the complete system and the achievement of highest efficiency.

Inverters, DC/DC converters and charge controllers are the central components both for processing the electricity from generators such as PV systems, wind turbines and combined heat and power (CHP) stations, and also for the system integration of electricity storage systems. Fraunhofer ISE develops highly efficient components for these applications in the power range from less than 100 watts up to the megawatt category. We have been an internationally leading research and development partner for industry in this sector for decades and can now draw on many patented circuit designs. Furthermore, we transfer our concepts and knowledge to other application areas such as medium-voltage technology, railway technology or power electronic components for use in space technology.

In many application areas, the demand for more powerful components at simultaneously lower costs is increasing continually. The search for new solutions has very high priority at Fraunhofer ISE as a partner for industry. The application of the most modern active and passive components such as transistors of silicon carbide or gallium nitride is particularly promising. Thus, it will be possible in future to work with switching frequencies up to the MHz range, which allows smaller inductivities to be used and thus significantly more compact and cost-effective configurations. Further challenges are posed by rising demands on the quality of output voltage and control properties, as well as the integration of additional functions such as the provision of reactive power.

Our efficient power electronic components are also indispensable in the electromobility sector. We have developed a bidirectional rapid charger with a power of 22 kilowatts and an efficiency value exceeding 98 %, which is so compact that it can be used both in external charging stations and also on board. Concepts from photovoltaics led to reduced volume and better product properties. In addition to cable-connected charging systems, we are also working on inductive high-power charging systems with rated power of more than 20 kilowatts. These can be used to meet future requirements on wireless charging of electric vehicles and provision of grid stabilization functions.

Fraunhofer ISE has comprehensively equipped laboratories with the most modern generators and measurement and testing instruments. Of course, all tests according to the relevant product standards and international grid feed-in guidelines can be carried out there. Together with industrial clients, we also conduct the low-voltage ride-through test to investigate grid voltage drops in the medium-voltage grid, which is possible in only a few laboratories. In addition, we also contribute with our extensive experience to international standardization work.

FURTHER INFORMATION

Staff	**47**
Full-time equivalent staff	**41**
Journal articles and contributions to books	**2**
Lectures and conference papers	**24**
Newly granted patents	**1**

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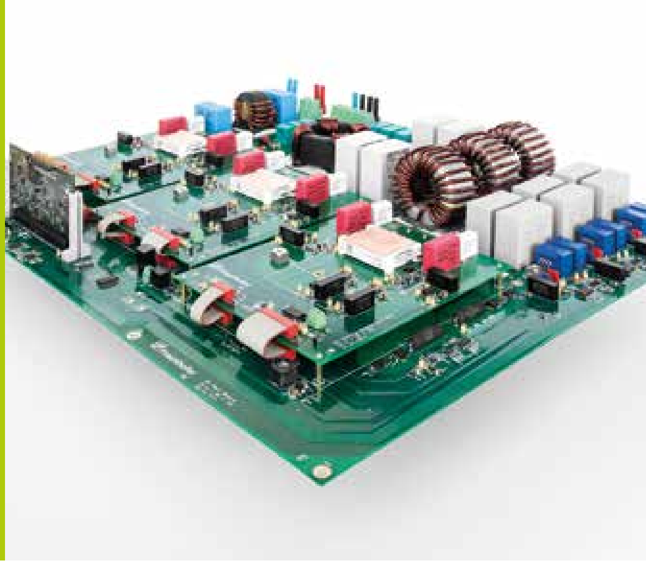

Three-phase PV inverter for use in the laboratory. The modular design allows the most modern circuit topologies and semiconductor modules to be tested efficiently. New control algorithms can be investigated under realistic conditions and optimized using the digital signal processor and extensive measurement data acquisition.

CONTACTS

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1

DC/DC CONVERTER TO CONNECT BATTERY MODULES EFFICIENTLY TO HIGH-VOLTAGE BUS

Electric storage units, which can compensate differences between generation and consumption, are very important for the expansion of renewable energy usage. Storage solutions are also needed in off-grid electricity systems and to operate electric vehicles. As battery cells have a low cell voltage, the voltage must be adapted for the intended application. In battery packs, higher voltages are achieved by hard-wired series connection of the single cells, meaning that the weakest cell limits the performance of all cells and one defective cell makes the whole battery pack unusable. A modular concept combined with intelligent power electronics can minimize these disadvantages. This leads to very reliable systems with low maintenance costs.

Michael Eberlin, Florian Reiners, Olivier Stalter, Günther Ebert

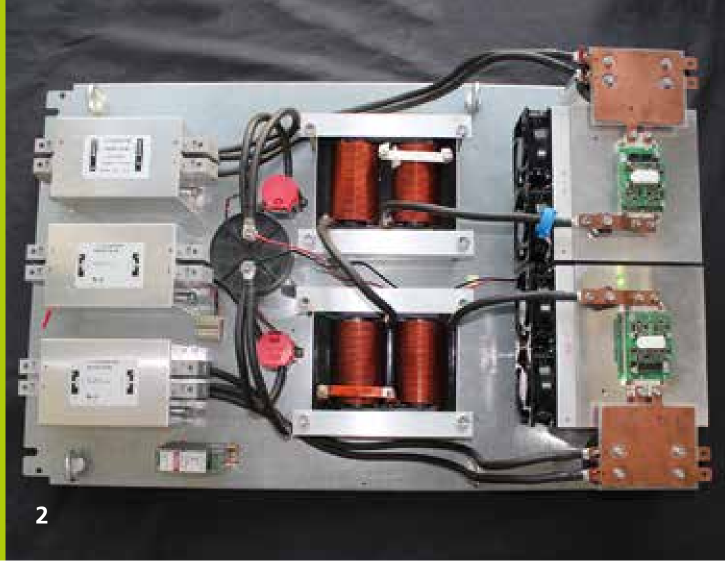
Different battery voltages in a battery storage system can be obtained by hard-wiring the single cells in series. The direct connection of battery cells in conventional systems is often the main cause of accelerated battery aging, which is accompanied by sinking system efficiency and increasing maintenance costs. It brings the disadvantage that a defect in a single cell results in outage of the entire storage unit. Production of the battery pack is complicated, as is the replacement of a defective single cell. This also leads to system losses, as the substitute cell cannot be fully exploited due to aging processes in the other cells.

Within the "Cell-Booster" project, a new technological approach is being investigated, which optimizes the energy and cost efficiency of the battery storage systems that are common today and should also simultaneously extend their operating duration and lifetime. The intended innovation addresses systems technology, with a focus on novel embedded electronics, the so-called "Cell-Booster". These power electronics are responsible for direct impedance matching and DC/DC conversion, which decouples the 48 V battery pack and forms a well-defined module. The modular construction not only improves the system efficiency but also makes it simple to implement a hybrid battery. In this way, storage systems combining lead-acid and lithium-ion batteries can be constructed directly and cycled individually, depending on their properties.

1 *First laboratory demonstrator of the embedded electronics with a switching frequence of 100 kHz for decoupled connection of 48 V battery packs to an 800 V high-voltage bus. The power electronics allows direct impedance conversion at the module level, leading to simple maintenance and optimal utilization of the individual battery packs. This significantly improves the energy and cost efficiency compared to the battery storage systems used today.*

Maintenance of the system is simple, as individual modules can be replaced even during operation. This ensures a long system lifetime, as a module with a defective cell can easily be replaced by a battery pack of the most recent generation with completely different properties. The power electronics unit was developed at Fraunhofer ISE using modern semiconductor components. A first demonstrator unit has been constructed (Fig. 1) and is being taken into operation. The project goal is to develop a demonstrator which can have its practicability investigated in a realistic test environment.

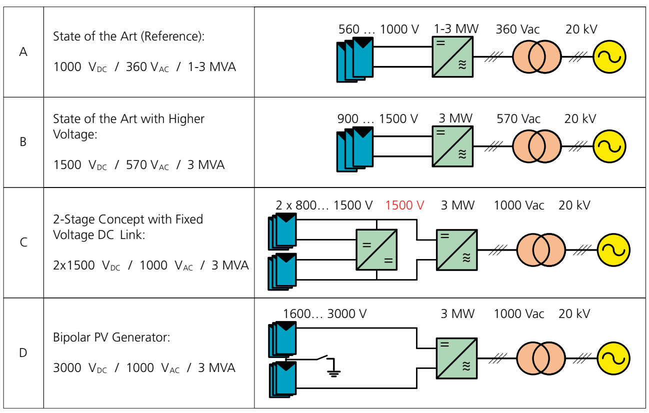
The project is supported by the German Federal Ministry of Education and Research (BMBF) within the "High-Tech" Strategy of the German Federal Government.



POWER ELECTRONICS FOR PV POWER STATIONS OF THE FUTURE

The maximum system voltage in PV power stations today is usually 1000 V. In the "HiDC-PV-Kraftwerke" project, power station technology is being developed which operates with the maximum possible voltages corresponding to the Low Voltage Directive. Appreciable savings in costs and resources can be achieved due to the correspondingly reduced currents. Different power electronics concepts with DC voltages of 1000 V to +/- 1500 V were compared to each other. Not only were the costs for the balance-of-system components (BOS) determined but also the efficiency of the power electronics systems was investigated.

Stephan Liese, Sönke Rogalla, **Stefan Schönberger**, Olivier Stalter, Günther Ebert



3 *Overview of the investigated power station concepts with a DC voltage level of 1000 V to +/- 1500 V. With the new concepts, the potential for a maximum AC voltage of 1000 V allowed by the Low Voltage Directive can be fully exploited.*

1 *Multi-megawatt PV power station.*

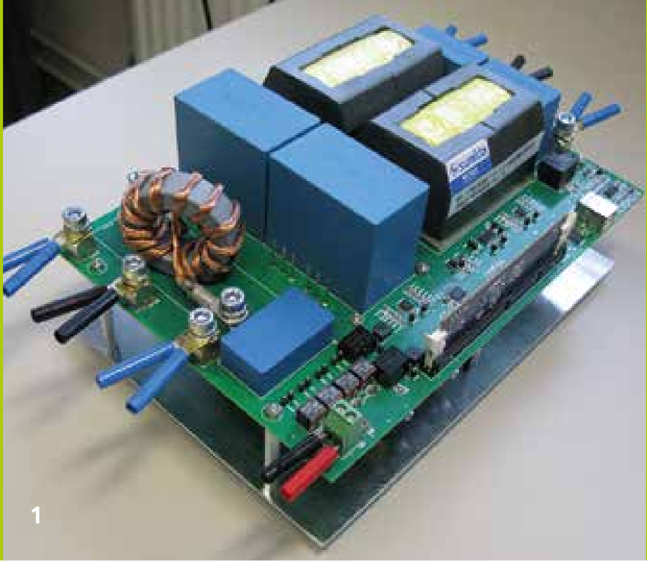
2 *Prototype of the DC/DC converter for use in large PV power stations.*

A power station concept corresponding to the state of the art was defined as a starting point (Fig. 3, Case A). In order to investigate the effect of the power on the costs, this concept was scaled up to 3 MW. This results in savings in the BOS costs of 16 %. The influence of the voltage level was demonstrated by analysis of three further concepts with raised voltage levels (Fig. 3, Cases B to D). Each of these three concepts leads to a further reduction in the BOS costs of 15 % compared to the 3 MW reference concept.

Simulation calculations were made to determine the losses and efficiency values of the concepts. A conventional 2-stage topology was simulated for reference case A, whereas a 3-stage topology was chosen for cases B to D due to the elevated voltage. In case C, the same power converter can be used as in case B, but featuring a rated power which is 50 % higher due to the fixed voltage operation. For case D, the power converter must be equipped with semiconductor components which can tolerate higher voltages. Efficiency values exceeding 98 % are possible with all topologies. Only case D showed weaknesses at high voltages.

For the DC/DC converter needed in case C, we have used an innovative topology which has great advantages compared to a conventional DC/DC converter. A prototype with a power rating of 250 kW and an efficiency value exceeding 99 % has already been constructed. In cooperation with the project partners, implementation of a 3-level power converter is planned.

The "HiDC-PV-Kraftwerke" project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).



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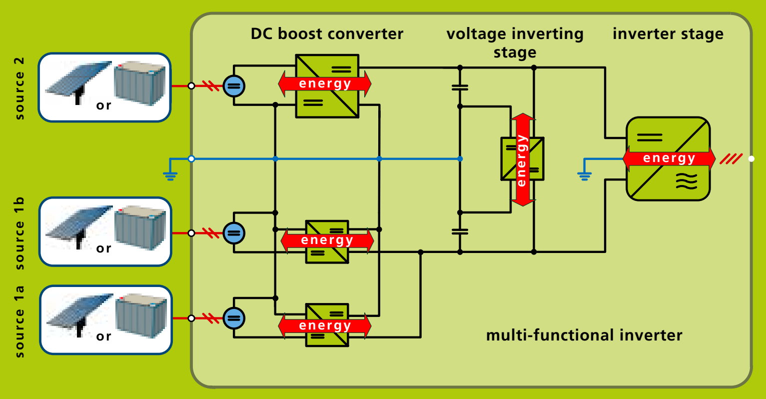


2

MULTI-FUNCTIONAL INVERTER TO OPTIMIZE ON-SITE CONSUMPTION

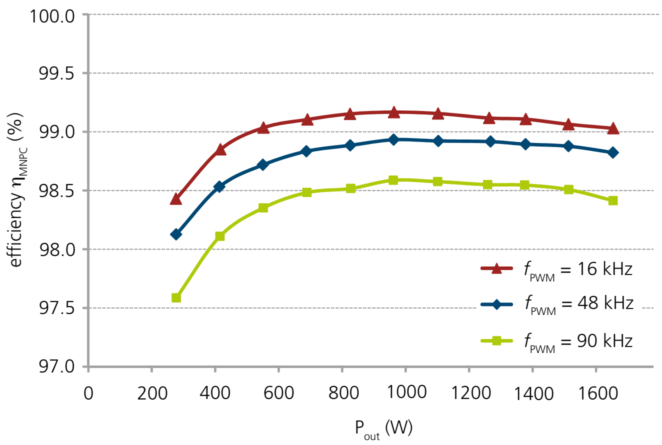
Rising electricity tariffs and significantly reduced feed-in tariffs according to the amended German Renewable Energy Act (EEG) are motivating increasing numbers of electricity consumers to consume their PV generated electricity on site. To make implementation technically simpler, we at Fraunhofer ISE have developed a very efficient three-phase inverter with innovative topology and three multi-functional inputs. The inputs can be connected as required to solar generators and / or batteries, so that all commonly available module and battery types (for voltages > 100 V) can be used. In this way, the user is able to choose the DC source flexibly, without needing complicated configuration of the inverter. Optimized on-site consumption is thus guaranteed.

Corentin Gasser, **Andreas Hensel**, Dirk Kranzer, Christian Schöner, Olivier Stalter, Günther Ebert

In order to integrate different DC sources into the system and implement all necessary energy flow paths, an innovative topology was chosen (Fig. 2). Due to its robustness against overloading, the system can also be used for stand-alone operation. In addition, we have developed controls with automatic source detection for all operating modes. The very compact demonstrator, with dimensions of 18.2 x 32 x 14.2 cm^3, contains all necessary components and converter stages. It was designed with minimal empty spaces and gaps between the components. The converter stages were implemented with power modules of silicon carbide transistors. The resulting switching frequency of 48 kHz, which was achieved in all conversion stages, meant that small board-mounted inductive components could be used, which leads to considerable cost benefits in production. In addition, the smaller dimensions of the passive components reduce the material demand and thus also the system costs. In order to save weight, an active cooling aggregate was used which can provide cooling on both sides for the AC and the DC power modules, making it efficient with respect to costs, energy and occupied space. The complete system weighs less than 10 kg. It consists of a four-part DC stage with three input boosters and a quasi-resonant inverting stage, the DC link and a three-phase inverter stage with 3-level topology. The individual efficiency values of the stages are each about 98.2 %, despite the high switching frequency of 48 kHz (Fig. 3).

1 *Demonstrator for the DC part of the multi-functional inverter with DC input components and the quasi-resonant voltage inverting stage.*

2 *Possible system configurations for the multi-functional inverter with a common earth connection.*



3 *Efficiency values for one phase of the inverter stage for different switching frequencies. The demonstrator was designed for a switching frequency of 48 kHz.*

The project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

ZERO-EMISSION MOBILITY

Electromobility is becoming increasingly visible in our everyday life: Concepts such as plug-in hybrid, battery-based electro-mobility, fuel-cell vehicle, recuperation, range extender or fast filling station are present in the media.

In our activities on Zero-Emission Mobility, we offer research services concerning both the drive energy and the necessary infrastructure. Our research encompasses:

- charging infrastructure for electric vehicles
- battery systems for mobile applications
- grid integration of electric vehicles
- fuel cell mobility
- hydrogen infrastructure
- heat management in vehicles

Vehicle batteries must be integrated into the Smart Grid in a way which takes account of the increasing demands by the electricity grid. We develop hardware and software solutions for communication interfaces to charging stations, for generation-adapted charging and to provide grid services. We offer both technological and economic analyzes and simulations of grid aspects.

Concerning traction batteries, we develop modules and systems with the necessary safety concepts and battery management systems. The thermal, electrical and electro-chemical behaviour is modelled from the cell level to systems, including aging models and life cycle cost analysis. We develop intelligent charging and operation management strategies which can be integrated into the microcontrollers of charge controllers, equipment controls and battery management systems.

Power-electronic converters form the links between the battery, fuel cell, drive unit and electricity grid. We offer comprehensive solutions for power-electronic systems for grid integration of electric vehicles. Our expertise is in the area of highly efficient and compact power-electronic converters and inductive and conductive charging systems.

Fuel-cell vehicles offer zero-emission mobility with a long driving range and short refuelling times. We support their development by characterizing single cells, cell stacks and systems. In addition, we test peripheral and cell components under extreme climatic conditions and with respect to their electrochemical stability.

Hydrogen can be produced by renewable electricity generators and electrolysis. We investigate and demonstrate this with our solar hydrogen filling station and two fuel-cell vehicles. We use this as a research platform for future mobility, component tests and holistic energy concepts. We provide advice on hydrogen infrastructure and develop innovative technology for membrane electrolysis. Test stands for cell stacks up to 1 MW_{el} are available for this research.

Efficient heat management plays a major role with regard to the durability and operating safety of batteries and fuel cells. We achieve efficient temperature control with new, high-performance materials. Our portfolio ranges from the development of new materials to store heat and cooling power, through their system integration, to heat management in vehicles.

The combustion engine will still be dominant in the immediate future. Thus, we develop and test catalysts for exhaust treatment. For alternative, (homogeneous) combustion processes to reduce emissions within the motor and exhaust gas treatment systems, we favour our patented process for residue-free evaporation of liquid fuels.

To support successful transition to Zero-Emission Mobility, we prepare intermodal mobility concepts and offer investigations on emission reduction in fleets of vehicles. Furthermore, we carry out studies to evaluate future mobility concepts and user acceptance.

FURTHER INFORMATION

Staff	**36**
Full-time equivalent staff	**34**
Journal articles and contributions to books	**5**
Lectures and conference papers	**8**

www.ise.fraunhofer.de/en/publications/55

Test drive with one of the two fuel cell vehicles belonging to Fraunhofer ISE.

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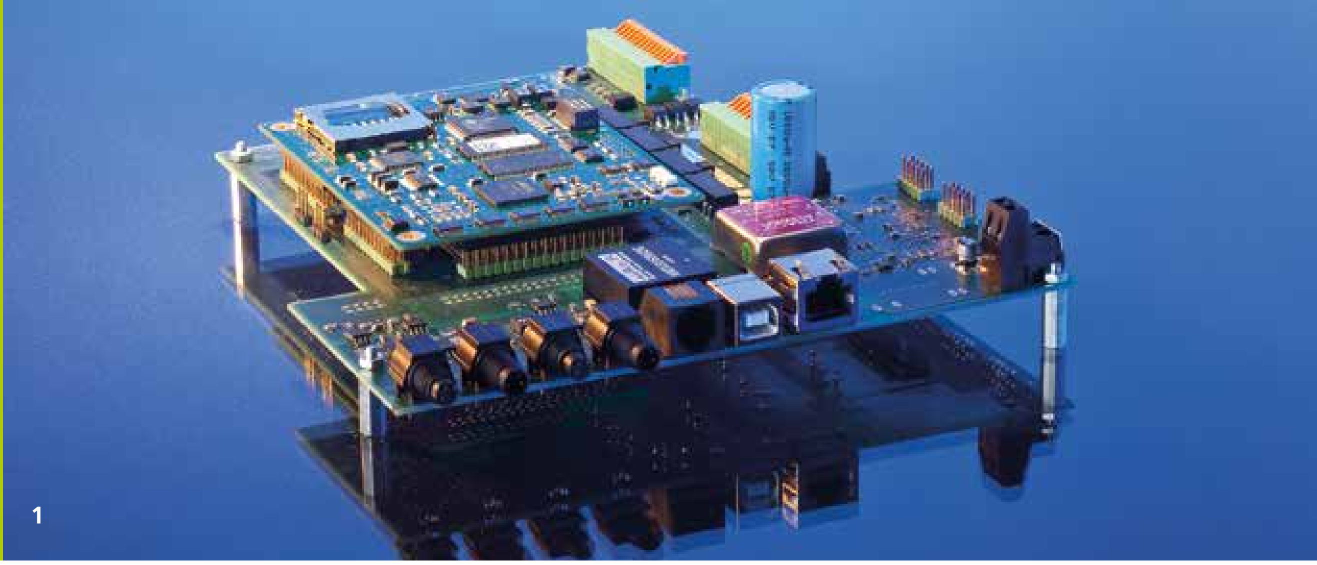


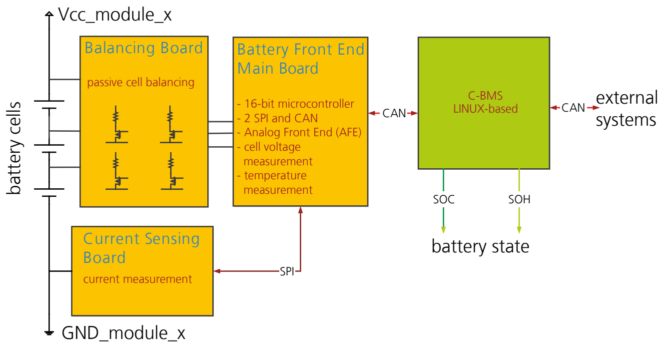
INNOVATIVELY STRUCTURED BATTERY MANAGEMENT SYSTEM

The future market success of electric vehicles depends crucially on the performance and quality of the automotive batteries used. In addition to design questions, cell selection, mechanical construction and the electric circuit, the central task concerns the battery management system as the "brain" of the battery system. It determines the state of charge and implements the safety features, meaning that it is primarily responsible for reliable and range-optimized operation of the vehicle.

Naqqash Abbassi, Nikolaus Lang, **Stephan Lux**, Peter Raab, Matthias Vetter, Günther Ebert

A battery management system provides the central intelligent control of a battery system. It prevents both overcharging and deep discharge of the battery system. Highly accurate voltage measurement of each battery cell and precise measurement of the current is the basis for determining the state of charge (SOC) and state of health (SOH) correctly. To this purpose, Fraunhofer ISE is developing stochastic filter processes such as so-called particle filters, which allow the SOC and SOH of each individual cell to be determined very accurately during operation. The basis for SOC determination is provided by battery models, which are parameterized and validated by measurements in the battery laboratory. At Fraunhofer ISE, a system is being developed which consists of one so-called battery front end for each battery module and the higher-level, central battery management system (C-BMS, Fig. 1). The front end provides not only measurement and cell balancing functions but also an intelligent connection via the CAN bus to the C-BMS. The cell balancing ensures charge equalization between the individual cells on the basis of highly accurate SOC determination.

1 *Central battery management system (C-BMS) for a lithium-ion battery system.*



2 *System architecture of the developed battery management system. The intelligent, highly accurate battery front end, which can easily be extended, communicates via the CAN bus with the central battery management system (C-BMS).*

Within the Fraunhofer systems research topic, "Electromobility II", the Fraunhofer-Gesellschaft is extending its successful work on electromobility.

In this context, Fraunhofer ISE is developing an innovative battery management system for a lightweight energy pack, which can guarantee safe and range-optimized operation by applying the features described above.

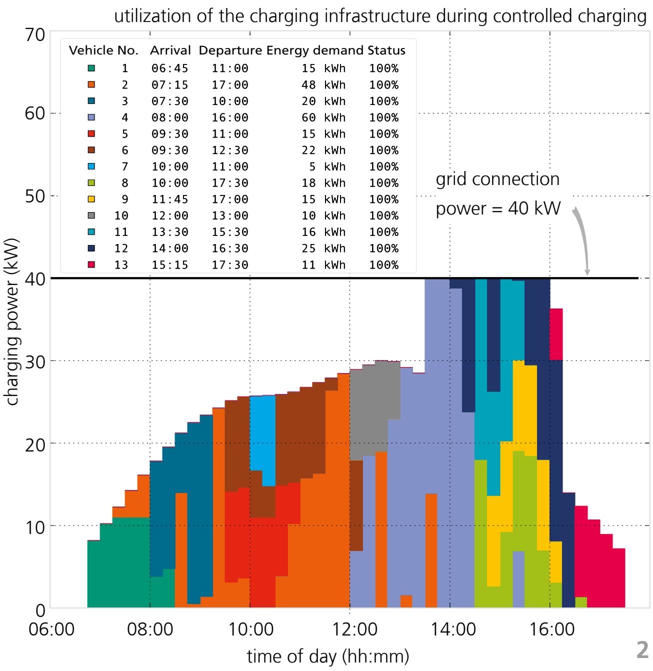
1

© Belectric

OPTIMAL INTEGRATION OF ELECTRIC VEHICLES

Increasing numbers of light-industrial energy systems with large electric and thermal loads are being extended with generation systems based on renewable energy and controlled by energy management systems (EMS). Often a fleet of vehicles also exists, most of which could be electrified. This type of fleet needs many charging stations on site. However, the total charging power for the fleet vehicles quickly exceeds the rated power for available grid connections. Innovative solutions from Fraunhofer ISE aim to ensure optimal charging operation within the rated power limits of the grid connection and to use the significant loads presented by the charging vehicles to the benefit of the existing EMS solution.

Felix Braam, Robert Kohrs, **Michael Mierau**, Günther Ebert



2

1 The "Innopark" light-industrial park in Kitzingen, the "Living Lab" of the "Intellan" project.

2 Application of the optimization algorithm to schedule the charging of each individual vehicle. The optimized charging schedules ensure that the grid connection is not overloaded and that the available PV-generated electricity is used optimally.

In the "Intellan" project, a light-industrial energy system with large, local, regenerative electricity generators (Fig. 1) is being extended with charging infrastructure for electric vehicles. Optimal load flow in the entire system is guaranteed by innovative operation management: Due to the flexible vehicle charging loads, the on-site consumption of locally generated PV electricity is increased and consumption peaks from the grid are reduced. In order to minimize the integration costs, the well-proven operation management of the light-industrial energy system has not been modified. Instead, state and control parameters have been identified, which can be used to influence the system behaviour. For the charging infrastructure, we have developed an optimization algorithm which – based on charging power bands – prepares charging schedules for the individual vehicles (Fig. 2). The energy management gateway can input various types of information – rated power of the grid connection, demand for the light-industrial loads, availability of electricity generated from renewable sources – into the optimization process via this abstract interface. We are applying our competence in self-learning systems and prediction-based operation management to the development of the energy management gateway. It is the intermediary between the charging infrastructure and the light-industrial EMS. The result is a modular complete system, in which the complexity of each sub-system remains transparent.

The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

CHARACTERIZATION OF AUTOMOTIVE FUEL CELLS

Automotive fuel cells have comparatively large cell areas and are operated at high current densities of up to 3 A/cm². This results in appreciable inhomogeneity over the active area, caused by the depletion of reaction gases and the increase in temperature and humidity due to the electrochemical reaction. In order to characterize these local effects scientifically, we apply our unique multi-channel impedance test stand and segmented fuel cells. Furthermore, we are investigating automotive fuel cell short stacks in the climatic chamber, where we can monitor the behaviour of all single cells simultaneously by means of electrochemical impedance spectroscopy.

Dietmar Gerteisen, **Ulf Groos**, Stefan Keller, Nada Zamel, Christopher Hebling

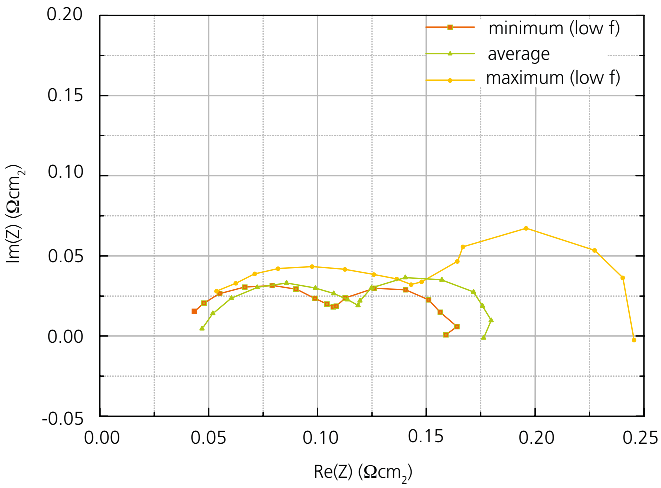
In cooperation with the Automotive Fuel Cell Corporation AFCC in Vancouver, which is responsible for fuel cell development within the Daimler group, we have separated a single cell of the fourth generation from 2009 into 68 electrically isolated segments. During potentiostatic operation, we can simultaneously measure the current and record electrochemical impedance spectra for each segment. We use this to investigate the local operating state as a function of the voltage, the operating temperature, and the stoichiometry and humidity of the reaction gases, when operation is started or stopped and during rapid load changes. The results are used for model validation, the optimization of operation management and design improvement.

At the same time, we are characterizing a fuel cell short stack of the same generation in our walk-in climatic chamber. In particular, we can electrically contact the single cells and record not only the single cell voltage but also the electrochemical impedance spectra of all cells simultaneously. The goal of the experiments is to analyze the effects at the single cell level during stationary or dynamic operation as a function of the operation conditions in a stack. Furthermore, comparison of the results from the segmented single cell and the stack enables us to gain better understanding of the connections between local phenomena and the operating state of the complete stack.

Our work is supported by the Fraunhofer-Gesellschaft.

1 *68-channel impedance facility for spatially resolved characterization of segmented fuel cells.*

2 *Test stand with a multi-channel impedance system to characterize fuel cell stacks and systems in the climatic chamber.*



3 *Characterization of an automotive fuel cell stack with regard to the single-cell impedance spectra.*

SYSTEM INTEGRATION AND GRIDS Đ ELECTRICITY, HEAT, GAS

The transformation of the German energy system into a CO_2-reduced energy supply confronts us with huge challenges for innovation. The energy scenarios of recent years have shown that this enormous task can be accomplished only by a suitable combination and integration of diverse energy systems and grid structures. The "Smart Grid" has been discussed for some time for electricity grids, which should enable optimal interaction of energy systems in the liberalized energy market. Fraunhofer ISE is conducting research on Smart Grids, where increasingly the typical energy sectors, "electricity, heat and gas", are being integrated for optimal interaction within the entire system.

Integration of the electricity and heating sectors allows compensation of the large fluctuations in the electricity grid which arise due to feed-in from renewable energy sources. For example, electricity generated by combined heat and power (CHP) systems can be shifted into the evening peak load period, or excess electricity can be converted into heat by heat pumps and electric immersion heaters. Operation management systems play a central role here, as the issue involves not only the provision of electricity and heat when it is needed, but also predictive management of storage systems. Thus, virtual power plants are already being applied today, which optimize the operation of electricity generation on the basis of spot market prices and weather predictions with the help of thermal storage buffers. With its "OpenMUC" Gateway, Fraunhofer ISE is developing the corresponding technology to integrate Internet-linked energy plants into the whole system.

Our research on neighbourhood concepts focusses on heat distribution grids which enable CHP systems and thermal storage to be integrated. The goal is to develop an optimization strategy for supplying energy to urban areas, with the primary energy demand as the main criterion and taking economic factors into account. Smart Energy Cities represent a still wider field. They aim for holistic optimization of the entire urban space by adapting the supply structure and mobility concept to the requirements of renewable energy supplies.

The modelling and simulation of energy systems and grids provide an important foundation to all activities in this area, as they allow the energy flows to be analyzed. They are also used to develop communications and control systems for the components and operation management technology. R&D work is concentrating on system-optimized integration of decentralized energy systems. The activities extend to autonomous power supplies and mini-grids, in which the focus is on storage management. The topics addressed also include decentralized water purification systems, which are often powered by solar thermal and PV systems.

Looking to the future, hydrogen technology will assume a central role in the structural changes to our energy systems. It promises to provide seasonal storage of renewably generated electricity by the coupling of gas networks and electricity grids. In power-to-gas technology, hydrogen is generated by electrolysis for decentralized storage or input into the existing gas network. At Fraunhofer ISE, a solar hydrogen filling station is operating, thereby demonstrating that all of the components needed to use hydrogen for zero-emission mobility are already available today.

FURTHER INFORMATION

Staff	**67**
Full-time equivalent staff	**52**
Journal articles and contributions to books	**14**
Lectures and conference papers	**20**

www.ise.fraunhofer.de/en/publications/45

The "Sonnenschiff" is the service centre for the solar settlement in Freiburg – and the first commercial premises to be designed as a plus-energy building.

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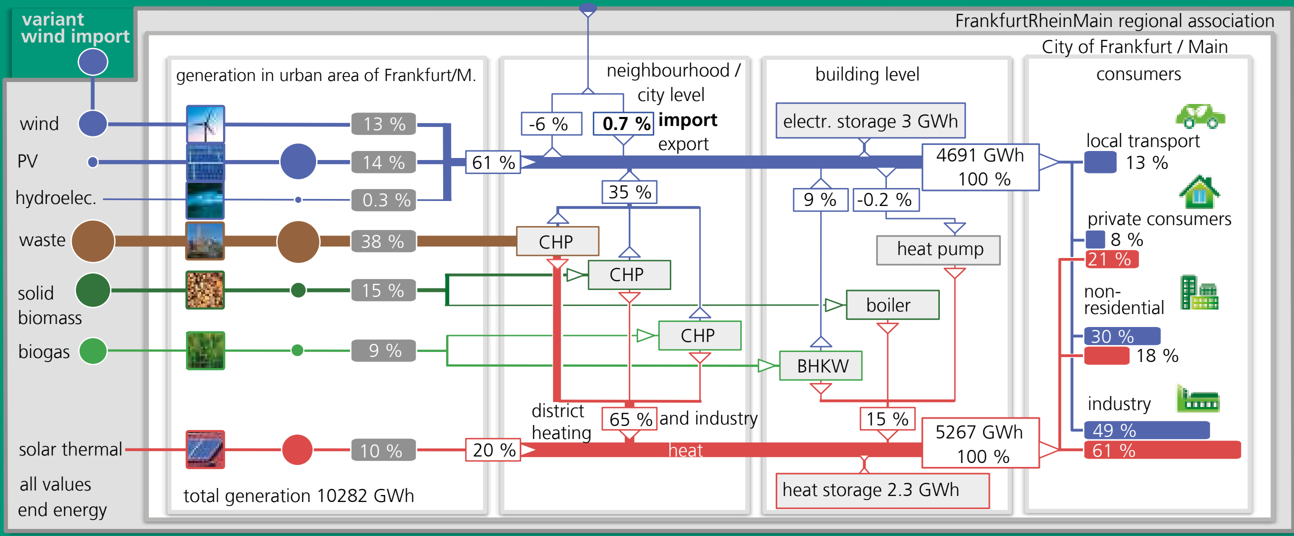

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ARE SUSTAINABLE ENERGY SYSTEMS POSSIBLE FOR OUR CITIES?

More and more cities have set themselves the goal of sustainable energy systems based on renewable energy sources. But how should the concrete target system be designed, if it is defined by large shares of fluctuating energy supplies and dynamic components such as storage units and cannot be fully implemented until 20 or 30 years in the future under substantially different boundary conditions to today? Fraunhofer ISE has developed an urban energy system model ("KomMod") which optimizes urban and regional energy systems with fine temporal resolution according to economic and / or ecological criteria, taking electricity, heat, cooling power and local transport into account. "KomMod" was used to calculate how the city of Frankfurt / Main could be supplied completely with renewable energy in 2050.

1 *Energy scenario for Frankfurt / Main in 2050, as calculated with "KomMod". Supply from renewable energy sources (including waste) from the city of Frankfurt and the Frankfurt-Rhine-Main region (grey background) and wind power drawn partly from a larger region is possible if electricity storage capacity of 3 GWh is present and a remainder of 0.7 % electricity is imported. The area of the circles representing the individual energy sources is proportional to their contribution. (CHP = combined heat and power plant)*

Jan-Bleicke Eggers, Sebastian Herkel, Annette Steingrube, **Gerhard Stryi-Hipp**, Hans-Martin Henning

The elements of a sustainable urban energy system are well known: high efficiency in generation and consumption, utilization of local renewable energy (RE) sources and increased flexibility achieved with Smart Grids and storage units. The local RE potential is not sufficient for medium-sized and large cities, so energy cooperation between cities and the surrounding regions is needed. The optimal configuration of the energy system, which can guarantee supply reliability at all times and take account of interactions between electricity, heat and transport, must be calculated. The boundary conditions in the target year, such as the retrofit status, demography, economics and technology, must be determined externally. Further, import and export restrictions and the geographical boundaries have to be defined.

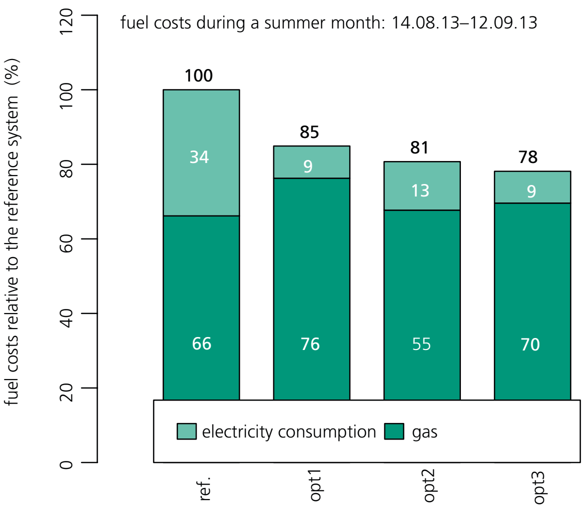
The city of Frankfurt / Main intends to be supplied completely by RE sources from within the city and surrounding region by 2050. Using "KomMod", the calculations demonstrated that a complete energy supply can be achieved if the RE potential in the city is used completely and that of the region is used partially. Complete autonomy is even possible. However, it is more efficient, cost-effective and flexible to allow import and export of electricity within certain limits. The calculated solution is illustrated in Fig. 1.

Particularly interesting features include the large share of energy derived from waste, which is collected from the surrounding region and combusted in Frankfurt, and the small share of wind energy due to its low potential. Other choices of input parameters lead to significant redistribution among the various sources. "KomMod" allows the relationships between input parameters and resulting solutions to be investigated.

MAKING HEAT, COOLING AND POWER SUPPLIES MORE FLEXIBLE

The energy supply of commercial buildings can be designed to adapt its behaviour according to the current availability of renewable energy in the electricity mix. Combined cooling, heat and power (CCHP) plants are well suited for this application, as they are able to consume electricity from the grid or generate it locally, depending on the situation. We are developing and testing a cold storage concept for a commercial building which supplies heat, cooling power and electricity efficiently, and favours the usage of electricity from renewable sources. A phase change material (PCM) cold storage with a very high energy density will allow optimal use of the limited space for storage in the building.

Stefan Gschwander, Sebastian Herkel, Doreen Kalz, **Konstantin Klein**, Martin Sonntag, Hans-Martin Henning



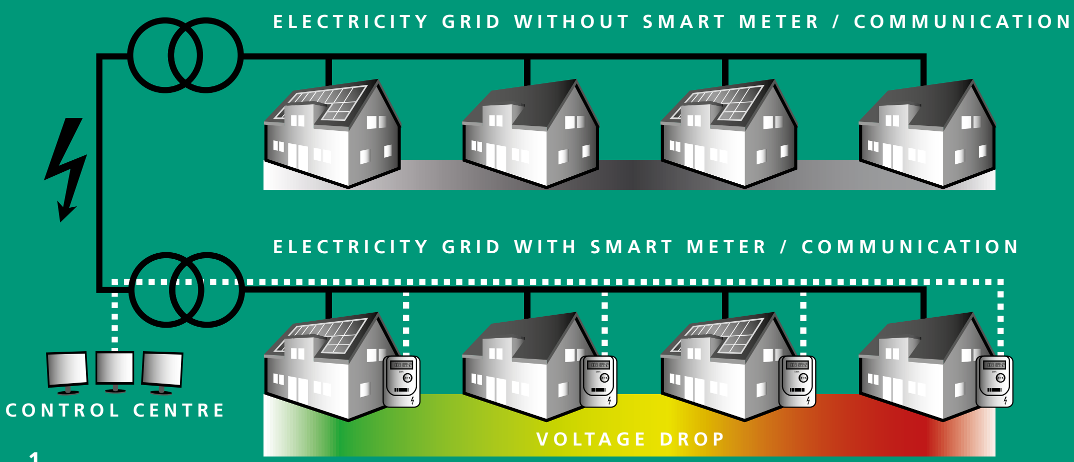
3 *Simulated operating costs for the building during a summer month. Ref: existing system, opt1: adapted CHP controls, opt2: improved utilization of CHP waste heat in the absorption chiller, opt3: system with PCM cold storage unit.*

1 *Absorption chiller, which can use excessive CHP heat as the driving energy for conversion into cooling power.*

2 *Compression chiller, which uses electricity to generate cooling power.*

The investigated system consists of three combined heat and power (CHP) plants, with 420 kW_{el} each, a peak-load gas-fuelled boiler, an absorption chiller and a compression chiller. Due to the technologies used, there is a strong mutual interaction between the various suppliers of heat, cooling power and electricity.

Since August 2013, a long-term monitoring project with fine temporal data resolution has been running to allow better insight into system operation and definition of concrete specifications for the storage unit in the investigated system. The acquired data serve both for operation analysis and to calibrate and validate dynamic simulation models of the system, which we use to develop optimized operation and storage concepts. Among other features, a salt hydrate PCM storage unit with a volume of 30 m^3 is foreseen. Compared to conventional water tanks, this storage unit offers the advantages of higher energy density and thus a more compact design. As space on site is very limited, a larger amount of cooling energy can be stored using the PCM technology than with water. After the storage unit has been implemented, its behaviour in real system operation will be monitored. The knowledge gained will be applied in the further development of PCM storage technology. Furthermore, we are analyzing the systems and control requirements for successfully integrating cold power storage into existing systems and for grid-supportive operation.



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OPTIMIZING THE UTILIZATION OF DISTRIBUTION GRIDS WITH SMART METERS

Electricity grids of the future will include intelligent electricity meters, so-called smart meters. An amendment to the relevant German law requires that smart meters must be installed in future in all households with electric vehicles, generators or an annual consumption exceeding 6000 kWh and all newly constructed buildings. The smart meters visualize consumption for the occupants and are intended to motivate them to save energy. The smart meters provide a communication channel between the grid operator and consumers, allowing incentives to be provided to shift electricity consumption into periods with large shares of electricity from renewable sources. In addition, the electricity grid operator can regulate the grid better on the basis of the newly available measured data.

1 *Two low-voltage grid sectors are represented. In the upper sector, smart meters are not used and the grid status is unknown. The lower sector is equipped with smart meters, such that it can be observed by the Control Centre and corrective measures can be taken if necessary.*

Wolfgang Biener, **Bernhard Wille-Haußmann**,
Christof Wittwer, Günther Ebert

The core of the smart meter system is a smart meter gateway, which enables communication between the connected equipment and to the external grid. Measurement instruments are connected to each gateway which record the power exchanged with the grid and its voltage. Controllable components are also integrated if present, e. g. electric vehicles, heat pumps and on-site generators. As conclusions can be drawn from electricity consumption profiles about the habits of the occupants, the smart meters are certified by the German Federal Office for Security in Information Technology.

The grid operator can read out data from the measurement instruments via the smart meter gateway and control the connected equipment to the extent agreed with the customer. Based on the acquired information, the grid operator is able to calculate the grid status. Fig. 1 compares two grid sectors. The upper sector represents the situation today without smart meters, where the grid status is unknown in detail. The lower sector illustrates a future electricity grid sector with smart meters, in which the voltage drop along the grid branch is visible. Knowledge of the prevailing grid status allows the grid operator to control connected equipment more efficiently and thus to make optimal usage of the grids according to their technical limits. For example, reactive power is used today to control the voltage in the electricity grid. However, this causes losses in the grid. Studies have shown that the data from smart meters can be used to parameterize the feed-in controllers for reactive power so specifically that these losses can be reduced by up to 50 % compared to otherwise typical standard installations. In addition, it is possible to determine whether grid extension is necessary after connection of new generators and loads. A disadvantage of smart meters is their relatively high cost. Scientists are currently discussing whether the cost-benefit ratio is acceptable.

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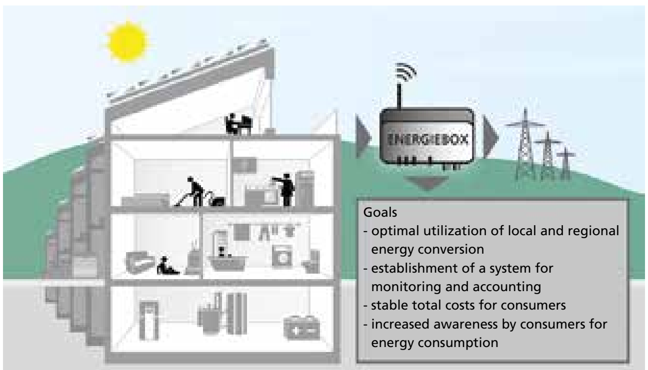
REGIONAL OPERATOR MODELS FOR DISTRIBUTED ENERGY SYSTEMS

Distributed energy converters and storage units allow different operator models to be implemented. Fraunhofer ISE is currently developing the "Energiebox" in cooperation with a regional utility, SWW Wunsiedel GmbH. The "Energiebox" consists of a spatially concentrated combination of different functions which are locally connected and matched to each other; generation / storage of electricity and heat, delivery and acquisition, remotely accessible and real-time measurement and monitoring. Together with its Enit Solutions GmbH spin-off and other external partners, Fraunhofer ISE is designing the communication links and possible configurations, simulating and evaluating different variants and contributing to cost-efficient operations management with optimization algorithms. The overriding goal is to investigate acceptance and – favoured by the participants' proximity to each other – potentially higher energy savings by the participating consumers.

Pascal Benoit, **Sebastian Gölz**, Raphael Hollinger, Niklas Kreifels, Günther Ebert



2 *Does the Energiebox encourage consumers to participate actively in the energy transformation? Is an operating model of this type lucrative for city utilities?*

1 *Aerial photograph of Wunsiedel.*

The "Energiebox" comprises several generators (combined heat and power, photovoltaic), storage units, controls and communication elements. It is a compact installation located mainly within a group of residential buildings (about 30 grid connections) in Wunsiedel. The goal is to meet the electricity and heating demand of these buildings on the basis of renewable energy sources and thus to reduce the load on the whole higher-level, regional energy supply provided by SWW Wunsiedel GmbH. On the one hand, Fraunhofer ISE is contributing to the modelling and simulation of the generators and consumers in the "Energiebox". On the other hand, the actual implementation of a remotely accessible measurement and monitoring system to acquire and store the real generation and consumption data is being undertaken together with our spin-off, Enit Solutions GmbH. The "Energiebox" facilitates a closer relationship between the participating households and the energy supply and demand, thereby encouraging greater awareness for energy usage. To further support the optimal exploitation of local or regional generation, an additional tariff structure is planned. The goal is to design the tariff and price structure such that the total costs for the participants remain stable but the local generation operation can cover costs. In addition to electricity generated on site, the "Energiebox" can also draw electricity from the higher-level grid or feed it in. This organizational aspect enables SWW Wunsiedel GmbH, the operator of the "Energiebox", to tap further efficiency potential within the Wunsiedel distribution grid. There, SWW Wunsiedel GmbH is operating further generators or has integrated them within the context of the German Renewable Energy Act.

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

www.energiewende-akzeptanz.de

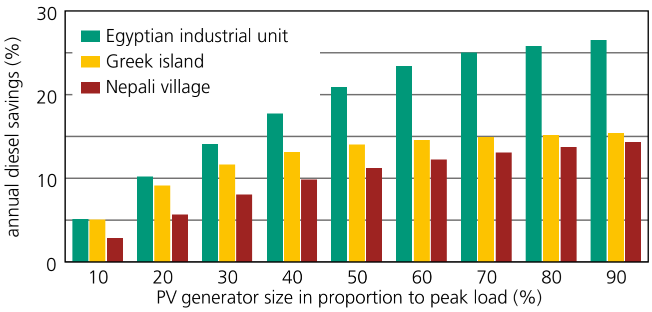
DIESEL-SAVING POTENTIAL DUE TO PV INTEGRATION IN DIESEL-BASED GRIDS

Many villages, towns, islands and industrial plants in regions around the world without grid access obtain their electricity from diesel generators. Replacement of these diesel generators by stand-alone PV systems is hindered by the high initial investment needed, although costs are saved on the long term. However, new approaches allow the total investment for stand-alone PV systems to be made not all at once but in small steps. Our simulation tools can visualize the diesel-saving potential and solar factor for this successive integration of initially standard grid-connected PV systems and subsequent extension with PV, "fuel savers" and the energy management system we have developed to optimize the complete system.

Björn Bayer, Georg Bopp, **Alexander Schies**, Matthias Vetter, Günther Ebert

Saving diesel in diesel-led off-grid electricity supplies begins with increasing energy efficiency and introducing a generator management system. The next step is integration of standard grid-connected PV systems. This can occur only up to a very limited share of PV to ensure that grid stability is retained. To increase the share of PV electricity within a diesel-based grid, a so-called fuel saver must be integrated. This reduces the input from the PV system if necessary, so that the diesel generator always runs with a pre-defined minimum load. The goal of our energy management system (EMS) is to avoid reducing PV input to the local grid by allowing direct consumption and to operate the diesel generators as efficiently as possible to minimize diesel consumption. We achieve this with our load management strategy, which activates diverse shiftable, switchable or variable loads like cooling loads or pumps according to an optimization algorithm such that the generated PV electricity can be used optimally. In order to visualize the diesel-saving potential, we have set up a simulation environment in Matlab® which includes diesel generators, fuel savers, loads and EMS. In three case studies (an Egyptian industrial plant, a Greek island and a Nepali village), we have calculated diesel savings in fuel-saver operation of between 5 % and 30 %. Our load management resulted in further saving potentials between 6 % and 15 %, depending on the loads present. Greater savings can be achieved by the fuel saver and EMS if the load profile matches the solar profile very well.

1 *Diesel generator to operate a pumping station near Aswan in Egypt. PV generators are amortized within a few years, saving diesel fuel and thus costs. New concepts such as fuel savers and energy management systems allow PV to be introduced successively, also without batteries, which greatly reduces the initial investment.*



2 *Diesel-saving potentials in diesel-led stand-alone systems with PV and fuel savers. Beyond a certain size of the PV system, saturation occurs and excess PV electricity is not accepted, because no storage unit is available and a minimum load must remain connected to the diesel generator. Our energy management system can shift this saturation limit upwards, so that more PV electricity can be used without changing the installed rated power.*

ENERGY SYSTEM ANALYSIS

Renewable energy technologies have developed rapidly in recent years: Prices have fallen dramatically, and at the same time, the installed power-generating capacity has increased greatly. In countries such as Germany, Italy and Spain, they already contribute significantly to the national power supply. Regions like North Africa and Asia are currently setting ambitious goals for expansion of renewable energy. There are many reasons for this: Environmentally friendly technology should help to protect the climate, meet the strongly growing energy demand cost-effectively, reduce dependence on expensive energy imports or conserve fossil resources for lucrative export.

Throughout the world, renewable energy technology – particularly photovoltaics and wind energy – has not only developed into an important industrial sector but also contributes with its growth to major changes in the energy system. In contrast to conventional power plants, the output from photovoltaic and wind energy parks varies with the availability of solar energy and wind. In order to even out the daily fluctuations in electricity generation, ways must be found to adapt generation and consumption to each other. The combination of different energy technologies or the integration of storage-coupled power plants can result e. g. in more constant electricity generation.

These changes stimulate new research questions, which mainly address the integration of renewable energy resources into the entire system: How can renewable energy resources be used cost-efficiently in different regions? How can different technologies be combined with each other to meet the energy demand optimally? In which direction will the energy system develop overall? Where should the public hand support this development? We offer a range of approaches to address these issues, which include:

- techno-economic assessment of energy technology
- market analysis and business models
- planning and operating strategies of power plants
- national and regional energy supply concepts
- modelling of energy supply scenarios

Different energy technologies are analyzed at Fraunhofer ISE according to technical and economic criteria such as the levellized cost of electricity. The application of renewable energy technology for an energy park or a country can be optimally dimensioned according to certain target criteria by investigating the interaction between the system components. Various methodological approaches are applied for energy systems analysis: A complete target system encompassing different sectors for a specified CO_2 reduction goal can be identified that creates minimum macroeconomic cost. Alternatively, an investment decision model can reveal how the energy system develops under certain boundary conditions and how the interaction between energy system components functions. In this way, our models provide a well-researched foundation for decisions on the boundary conditions for a future power supply.

Another instrument for analyzing energy systems is provided by business models, which we develop for different markets, taking account of the varying boundary conditions. We prepare recommendations on ways in which renewable energy technologies can be used more widely in future, also in countries in which they are not yet strongly represented. In this way, we offer comprehensive methods and tools to meet the challenges which a transforming energy system presents.

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www.ise.fraunhofer.de/en/publications/65

Pumped-storage hydroelectric power station in Rönkhausen with a power rating of 140 MW.

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TRANSFORMATION ROUTES FOR THE GERMAN ENERGY SUPPLY

Optimization calculations using the "REMod-D" model developed at Fraunhofer ISE have demonstrated which configuration a cost-optimized energy supply can have to achieve the goal of 80 % reduction in energy-related CO_2 emission in 2050. Our current research is now addressing the question: How can this goal be achieved over the course of time and how much will the transformation cost from now until 2050? To this purpose, the current stock of energy supply plants and possible expansion until 2050 were analyzed with respect to costs and dimensions. This revealed that the transformation saves costs increasingly and massively reduces dependence on fossil fuels.

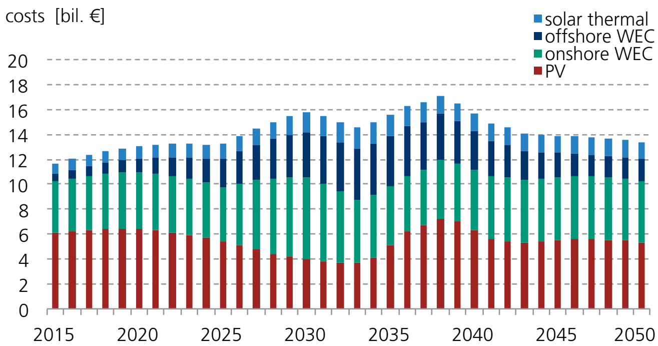
Benjamin Köhler, **Andreas Palzer**, Karoline Preiser, Hans-Martin Henning

The central goal for the energy transformation in Germany is to reduce the emission of greenhouse gases drastically. The intention is to reduce the emission level of 1990 by at least 80 % by 2050. Results from calculations with our "REMod-D" model showed that this is possible with expansion of photovoltaics (PV) to app. 150 GW_{el}, wind energy converters (WEC) to app. 150 GW_{el} (onshore and offshore) and solar thermal systems (STS) to app. 70 GW_{th} in combination with energy efficiency measures and further system components such as storage units and combined heat and power (CHP) generation.

Starting from the installed power existing for such systems in 2013 (app. 36 GW_{el} PV, 33 GW_{el} WEC und 10 GW_{th} STS), between 10 and 17 billion euros must be invested annually until 2050 in new construction and repowering (Fig. 1). The accumulated costs (without cost of capital and without extension of the required distribution grids) amount to app. 512 billion euros with this scenario. At the same time, the increasing substitution of fossil fuels will reduce dependence on imports and avoid the costs for buying fossil-fuelled energy. Assuming constant prices for fossil fuels, the expansion of renewable energy supplies will avoid expenses of app. 660 billion euros until 2050 (app. 1045 billion euros for an annual price increase of 2 %). The initially high financial outlay to transform the energy system will thus be compensated by avoided costs for fossil fuels and will lead to a more cost-effective energy system over the course of time.

1 Large photovoltaic system.

2 Reflections from PV modules of wind energy converters.



***3** Necessary annual investments in renewable energy to reach the target system with 150 GW_{el} photovoltaic systems,150 GW_{el} wind energy converters and 70 GW_{th} solar thermal systems (PV: photovoltaics, WEC: wind energy converters).*

1

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OPERATOR MODELS FOR ELECTRICITY STORAGE

In Germany, electricity from renewable energy sources already meets a quarter of the demand. However, the fluctuating availability of such electricity poses a challenge to the scientific and business communities. In future, energy storage options will thus be even more important than now. A project on operator models for electricity storage, involving Fraunhofer ISE, the Institute for Energy Economics and Rational Use of Energy IER and the Compare Consulting company, is addressing the described problem from technical, economic, ecological and social perspectives. The goal is to develop operator models for profitable application of electricity storage technology in the State of Baden-Württemberg.

Niklas Hartmann, **Verena Jülch**, Jessica Thomsen, Thomas Schlegl

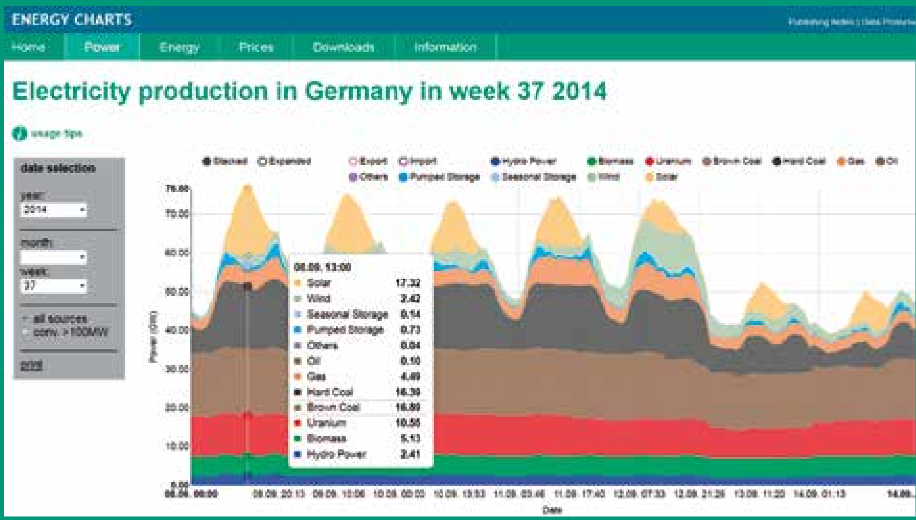
More than 30 pumped-storage hydroelectric power stations are operating at present in Germany. Due to the economic conditions, however, planned projects are currently being discontinued and there is discussion of closing down power stations that are already in operation today. Similarly, it is difficult to economically justify investments in battery storage units, which is the reason that the German Federal Government is now subsidizing their application in private households. There are many diverse operator models for renewable energy technology, e. g. energy cooperatives or contracting models, which have strongly promoted the introduction of this technology in recent years. Nevertheless, there have been very few innovative models at this level for electricity storage.

A project on operator models for electricity storage, involving Fraunhofer ISE, the Institute for Energy Economics and Rational Use of Energy IER and the Compare Consulting company, is addressing this situation and aims to develop operator models for profitable application of electricity storage technology in the State of Baden-Württemberg. We are examining four different types of requirements for the storage systems: technical, economic, ecological and social.

1 *Pumped-storage hydroelectric power station in Rönkhausen with a power rating of 140 MW.*

Different supply tasks for electricity storage units are being investigated in the project. They range from a free-standing house, for which e. g. the share of locally generated electricity consumed on site should be increased, through municipalities which aim to meet their energy demand autonomously, to the whole State of Baden-Württemberg, for which e. g. guaranteeing system stability has the highest priority. The different tasks lead to different technical configurations for storage concerning dimensions and operating modes. Economic calculations are made for different configurations and operator models, from home-owner through contracting to cooperative models, to determine their economic feasibility. In addition, the expected environmental impact of storage technology is being determined by life cycle assessment. Three workshops will be held as part of the project in order to involve the population, potential investors and other interest groups in the development process. These activities will provide a basis for the economic, ecological and socially acceptable development of storage projects in Baden-Württemberg.

The project is supported by the State Ministry for the Environment, Climate and Energy Economy in Baden-Württemberg.



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FRAUNHOFER ISE "ENERGY CHARTS": NEW WEBSITE WITH INTERACTIVE ENERGY DATA

Fraunhofer ISE launched a new transparency website with interactive energy data this year. Under www.energy-charts.de, visitors can create their own graphs: power, energy, electricity exchange prices and the import and export between Germany and neighbouring European countries can be displayed for different periods of time. In addition, individual energy sources can be included or excluded and percentage or absolute values can be read using a dynamic scale. Data sets from many different sources are evaluated and visualized in a clear format. The goal is to support discussions about the German energy transformation with facts and thereby contribute to rational treatment of the subject.

1 *Project website: www.energy-charts.de*

Bruno Burger, **Johannes Mayer**, Alexander Schultz, Thomas Schlegl

Already in 2011, the team headed by Prof. Bruno Burger started to provide weekly sets of graphs on electricity generation in Germany. From the beginning, the analyses were based on hourly resolved time series of electricity generation according to energy resource (brown coal, black coal, nuclear energy, gas, wind, hydroelectricity, photovoltaics). A new feature was that the time series were scaled with statistically determined correction factors before graphical presentation, because not all power stations are required to supply their generation data on an hourly basis. By applying the correction factors, very good coverage of the total power generated from the individual energy sources is achieved. The analyses have been continually extended since then and new categories have been added, such as the import and export of electricity, the relative utilization factor of the power stations and the development of electricity exchange prices.

By combining these data sets, scientists are able to investigate how the individual types of power station perform within the whole system and which steps are needed to improve the integration of renewable energy sources into the entire system.

The development of the new "energy charts" transparency website included a new technical base for visualizing the energy data and has already been received very favourably. The interactive approach allows users to create individual graphs for the first time and use them for their own analyses. Further graphs and new evaluations are planned for the future.

www.energy-charts.de

SERVICE UNITS

As a complement to our research and development work, we offer testing and certification services to clients. At present, Fraunhofer ISE has five accredited testing or calibration laboratories:

- TestLab Solar Thermal Systems
- TestLab Solar Façades
- TestLab PV Modules
- CalLab PV Cells
- CalLab PV Modules

Our TestLab Power Electronics is currently undergoing the accreditation process. The increasing proportion of electricity from renewable sources demands efficient power electronic circuits to connect electricity generation, storage and consumption. Reliability and compliance with standards by the components play a central role for acceptance and economic success of renewable energy in the electricity mix. In this context, we have upgraded the previous service units for inverters and power electronics to form the accredited TestLab Power Electronics.

Further service laboratories are drawn from the entire spectrum of R&D topics at Fraunhofer ISE, ranging from quality control of photovoltaic power stations through system integration and Smart Grid topics to storage technology, as well as heat transformation topics and fuel cells.

- TestLab Power Electronics
- ServiceLab PV Power Plants
- ServiceLab Smart Energy
- ServiceLab Batteries
- ServiceLab Lighting and DC Appliances
- ServiceLab Heat Pumps and Chillers
- ServiceLab Heat Exchangers
- ServiceLab Phase Change Materials
- ServiceLab Thermochemical and Porous Materials
- ServiceLab Air Handling Units
- ServiceLab Fuel Cells

These laboratories offer services to the industry with their specific equipment for measurement and testing. The following pages give an overview of the services offered by the different laboratories.

Beyond the service aspect, these laboratories also have a research function. The insights gained during characterization, 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.

In our TestLab Power Electronics we offer the characterization of generating units according to national and international grid codes. Furthermore, the efficiency of power-electronic equipment can be determined with high accuracy.

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CALIBRATION OF SOLAR CELLS ACCORDING TO INTERNATIONAL STANDARDS

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

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

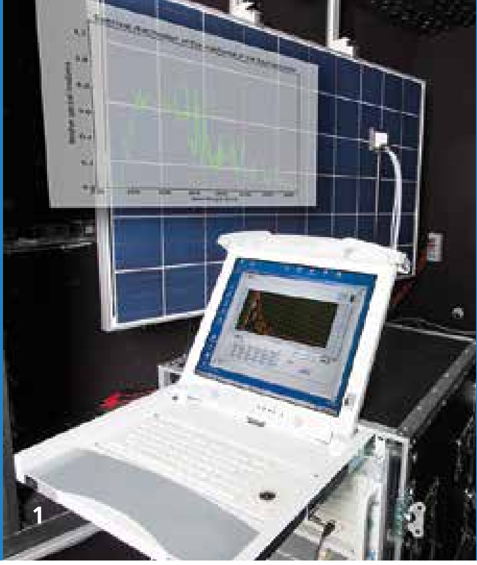
CalLab PV Cells is accredited according to ISO/IEC 17025 as a calibration laboratory for solar cell calibration with the Deutscher Kalibrierdienst (DKD). With the support of the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB), and in cooperation with PV manufacturers, we work continuously on improving tolerances and developing new measurement procedures. The change in solar cell parameters at higher temperatures plays an important role for their yield in practical applications. A new procedure, with which temperature coefficients can be determined with a previously unattainable accuracy, has proven to be very attractive for manufacturers of solar cells. Its special feature is measurement of the temperature-dependent spectral response. We intensively apply this and other special measurements in a project to optimize the maximum annual yield of high-efficiency solar cells by highly accurate analysis based on the dependence of cell parameters on temperature and irradiance level. The excellent cooperation with colleagues developing and analyzing high-efficiency solar cells is an important pre-requisite for this work.

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

In order to guarantee the comparability of measurements for solar cells from different types of PV technology, we are continuing to develop measurement procedures for novel solar cells. Cells with back-surface contacts or bifacial structures are particularly important. Organic solar cells and thin-film cells, especially those with multi-junction cell structures, also present a particular challenge. To meet it, we have taken advantage of our experience with the calibration of multi-junction solar cells for space and terrestrial concentrator applications. By extending our facilities for calibrating multi-junction cells of thin-film materials, we were able to support the rapid development of this technology still better with accurate measurements. The spectral response or the external quantum efficiency of multi-junction solar cells is determined 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 of dual and triple cells with our triple-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 developing calibration routines for solar cells with more than three pn junctions, among other projects, also as a member of working group WG 7 of technical committee TC 82 of the IEC.



WORLDWIDE MOST ACCURATE CHARACTERIZATION OF PV AND CONCENTRATING PV MODULES

As a result of comprehensive analyses and optimization, the measurement and testing laboratory, CalLab PV Modules, has improved its measurement accuracy to 1.6 %. An international comparison with leading laboratories around the world, namely NREL (USA), AIST (Japan) and JRC (Italy), has confirmed the excellent reproducibility of our measurements. CalLab PV Modules has thereby increased its international lead with regard to the precision of its PV module measurements.

Daniela Dirnberger, Ulli Kräling, Klaus Kiefer,
Frank Neuberger, Michael Schachtner, **Gerald Siefer**,
Harry Wirth

A smaller measurement uncertainty raises confidence in the measurement results and increases their usefulness. This is of equal benefit to module manufacturers and project developers, banks and investors. For example, the lower measurement uncertainty affects the measurement accuracy of a module manufacturer positively and thus increases confidence in specifications on labels and data sheets.

For our international clients who use the module measurements for quality control of PV power stations, the improved measurement accuracy also brings advantages. Banks and investors profit from precise measurements because they increase the probability of a certain return of investment. The measurement uncertainty of the testing laboratory often affects the pass / fail criterion for module power in projects and is thus the decisive parameter for evaluating the modules used.

Furthermore, clients who commission our certification tests, long-term evaluations and degradation analyses also profit from the highest measurement accuracy. The risk of unjustified rejection of a tested module type during a certification test is lower. In tests accompanying development processes, degradation effects can be recognized earlier.

1 *Accurate measurement of the solar simulator spectrum as the basis for the smallest measurement uncertainty among internationally leading calibration laboratories.*

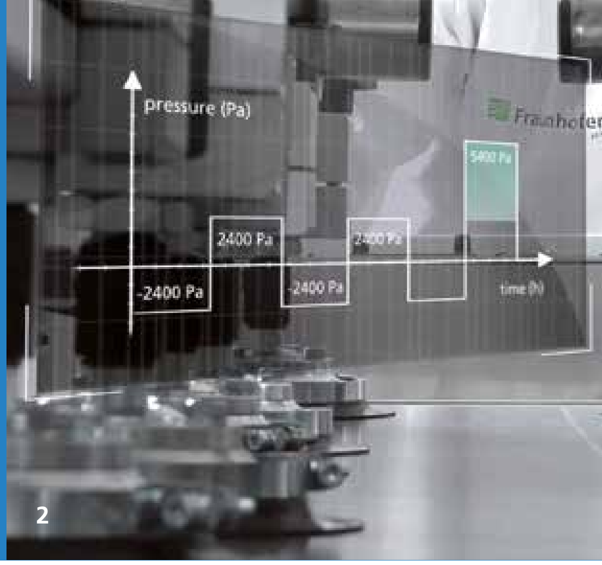
2 *Temperature-controlled chamber integrated into the solar simulator for precise characterization of PV modules for power rating according to IEC 61853-1.*

In addition to accurately determined power, other properties of PV modules significantly influence the yield of a PV system. In particular, these include initial light-induced degradation (LID) and the performance of the module under low light levels and different temperatures. Based on these power-rating measurements, the energy yield of PV power plants at any location around the world can be predicted accurately. CalLab PV Modules supports module manufacturers, EPCs (engineering, procurement, construction) and investors in quality control of their products around the world.

Measurement of concentrator modules

We operate several tracker units equipped with measurement data acquisition systems to characterize concentrator modules under outdoor conditions. In addition, a laboratory test stand is available to measure concentrator modules. This allows us to determine the efficiency value of concentrator modules under standard conditions. However, the methods to do so are not yet included in an international standard. We therefore participate actively in Working Group 7 of Technical Committee 82 of the IEC (International Electricity Commission) to further develop international standards on concentrator photovoltaics.

www.callab.de



COMPREHENSIVE MODULE TESTS IN TESTLAB PV MODULES

TestLab PV Modules offers a broad spectrum of services centred on quality and reliability testing. Our laboratory, which is accredited according to ISO 17025, is equipped with extremely modern and innovative testing facilities. Many years of scientific experience in lifetime analysis mean that we can advise our clients competently and independently.

Stefan Ali, Holger Ambrosi, Heinrich Berg, Ilie Cretu, **Claudio Ferrara**, Georg Mülhöfer, **Daniel Philipp**, Sandor Stecklum, Carola Völker, Jeanette Wolf, Harry Wirth

TestLab PV Modules was founded in 2006 as a service unit of Fraunhofer ISE. In cooperation with the Service Lifetime Group, we develop tests and procedures to guarantee the quality and reliability of PV modules. To do this, we use innovative facilities which can be applied for purposes extending well beyond the standard tests. This allows us to simulate degradation factors very realistically. We offer the following services:

Consultancy and testing specific to clients' requirements and applications

Individual questions require individual answers. Accordingly, we offer our clients competent, relevant services. Finding individual and cost-effective solutions for each client always has the highest priority for TestLab PV Modules, regardless of whether it concerns comparative module testing (benchmarking) or assessing the suitability of a specific type of module for particular application conditions.

1 *In the combined UV and damp-heat climatic chambers, PV modules can be subjected to a maximal UV dose of 200 Wm^{-2} under maximum conditions of 60 % relative humidity and 90 °C temperature for accelerated aging. Thus, not only standard test conditions but also the simultaneous effect of several degradation factors can be simulated.*

2 *Mechanical-load test facility. With it, tests conforming to IEC standards and tests which go beyond these can be carried out automatically (maximum pressure and suction of 10 kPa, maximum frequency of 0.2 Hz).*

Assessment and analysis of defects, risk minimization

Potential Induced Degradation (PID), so-called snail trails and problems with insulation are only a few of the typical defects which clients often present to us. We offer the option of analyzing these and other defects systematically and identifying causes and effects. Our goal is to reduce the occurrence of such defects. Thus, TestLab PV Modules offers specific tests and test sequences for many typical defects.

Quality control according to international standards

In close cooperation with our partner, the VDE Prüf- und Zertifizierungsinstitut, we certify modules according to international quality and safety standards (IEC 61215, IEC 61646, IEC 61730). We contribute to further development of these standards by participating in international working groups.

www.testlab-pv-modules.com

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TESTING AND DESIGN SUPPORT IN TESTLAB SOLAR THERMAL SYSTEMS

TestLab Solar Thermal Systems is recognized as an authorized testing body by national certification institutions around the world, and is fully accredited according to ISO 17025 by DAkkS (Deutsche Akkreditierungsstelle). We test solar collectors, thermal storage tanks and complete systems, thereby supporting our clients around the world in developing solar thermal systems.

Sven Fahr, Konstantin Geimer, **Korbinian Kramer**, Stefan Mehnert, Arim Schäfer, Christian Schmidt, Christoph Thoma, Werner Platzer

Our large test stand for mechanical loads has been operating since 2012. It has already been used to investigate numerous questions relating to the structural stability of mounting systems, PV modules and solar thermal collectors. The test stand is integrated into a climatic chamber, so very diverse mechanical load constellations can be tested at specific ambient temperatures (from -40 °C to +90 °C). Services in accordance with the requirements of the DIBt (German Institute for Building Technology) are also offered here. Special features of this test stand include the large testing area of 3 x 5 m^2, the possibility to apply heavy loads of up to 10 tonnes and reproduction of different load scenarios, e.g. cyclic loads, load gradients, dynamic loads. It should be noted that we already meet the requirements for a notified body as defined in the EU Construction Products Regulation.

Comparative investigations of PVT (PV thermal) hybrid collectors were continued. In combination with TestLab PV Modules, we are thus able to offer complete certification of PVT collectors.

1 *The outdoor test field of TestLab Solar Thermal Systems at Fraunhofer ISE in Freiburg.*

2 *Test stand for mechanical loads.*

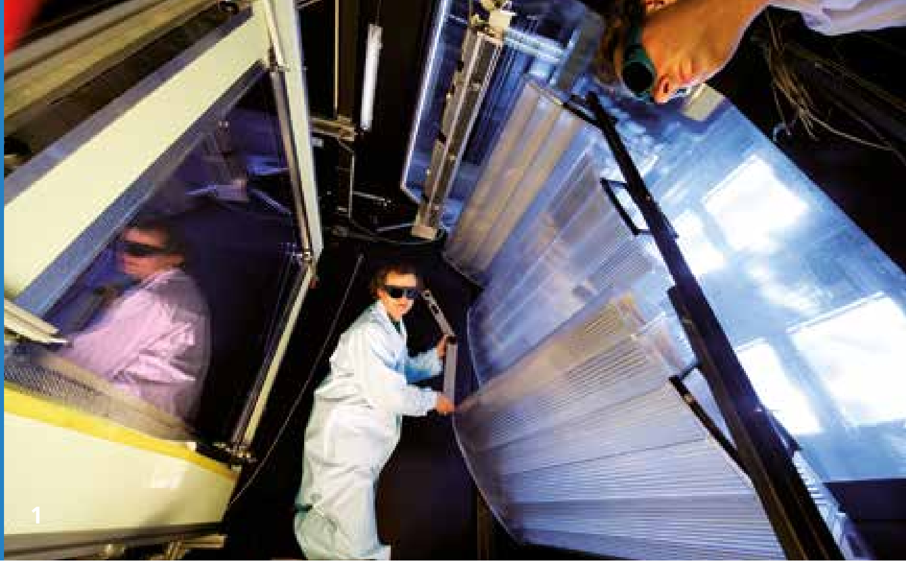
Our already established solar air-heating collector test stand was used intensively. With it, similar technical characterization to that for collectors with liquid heat-transfer media and Solar Keymark certification thus became feasible this year.

System investigations, particularly tank measurements, can be carried out in our systems and storage tank laboratory. This is where the coefficients are determined to evaluate tanks according to the Energy Label (ErP) of the EU. Our solar simulator continues to achieve the accustomed high reproducibility.

In combination with our precision tracker, we applied our medium-temperature test stand to measure efficiency characteristic curves for operating points up to 200 °C. In 2014, we succeeded in characterizing a large, concentrating collector in situ. This was a new application for TestLab Solar Thermal Systems within the context of extended collector certification.

In 2014, the new version of EN ISO 9806 became effective, one of the most important fundamental standards for our work. TestLab Solar Thermal Systems was directly able to accommodate all of the collector technologies that were newly included in its scope and to implement all changes to the testing methods within the scope of its accreditation.

www.kollektortest.de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MEASUREMENT OF BUILDING FAÇADES AND TRANSPARENT COMPONENTS

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

Ulrich Amann, Bruno Bueno, Johannes Hanek, Angelika Helde, **Tilmann Kuhn**, Christoph Maurer, Helen Rose Wilson, Hans-Martin Henning

We characterize transparent and translucent materials. We test building components, e. g. glazing units, and evaluate the energy-relevant, thermal and optical properties of complete façades. The following measurement facilities are available:

- solar calorimeter to determine the total solar energy transmittance, also for active-solar façades
- photogoniometer to determine the bi-directional scattering distribution function (BSDF) of transparent, translucent and light-redirecting components
- efficiency measurement
- thermal transmittance measurements (U value) of glazing units
- angle-dependent transmittance and reflectance measurements with large integrating spheres, both broadband and spectral
- UV-vis-NIR spectrometers to determine the spectral properties of glass, films and surfaces

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

The laboratory has been accredited according to DIN EN ISO / IEC 17025 since 2006. It is a so-called "flexible accreditation", which encompasses not only standard procedures but also the further-reaching procedures developed at Fraunhofer ISE to determine g value, transmittance, reflectance and U value. The German building code recognizes 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 optimization of controllers can be experimentally validated.

MEASUREMENT OF POWER ELECTRONICS ACCORDING TO INTERNATIONAL STANDARDS

In the course of the German energy transformation, we are experiencing far-reaching changes to energy systems. Power electronic circuits are at the centre of this development, acting as links between generators, storage units and consumers. Their acceptance and economic success depend crucially on high efficiency and reliability, as well as compliance with all relevant standards and grid codes. In our TestLab Power Electronics, we characterize power generating units according to national and international grid codes. Furthermore, the efficiency of power electronic equipment can be determined very accurately.

Florian Ackermann, Nicolas Bihler, Gregor Dötter, Sönke Rogalla, **Roland Singer**, Olivier Stalter, Frank Weichelt, Edgar Wolf, Günther Ebert

Megawatt Laboratory

Power electronic equipment with a power rating of up to 1 MW can be operated in the Megawatt Laboratory. A PV generator simulator with power of 1.4 MW is available for this purpose. A highly accurate measurement system with a broad dynamic range is used, which can record currents of up to 5000 A. To operate grid-connected power converters, the laboratory is equipped with a connection to the 20 kV medium-voltage grid and several feed-in transformers, each with a power rating of 1.25 MVA. The voltage of the transformers can be varied from 255 to 790 V. The laboratory has test facilities for "Low Voltage Ride Through" (LVRT) and "High Voltage Ride Through" to investigate dynamic grid support of power converters.

Field Measurements

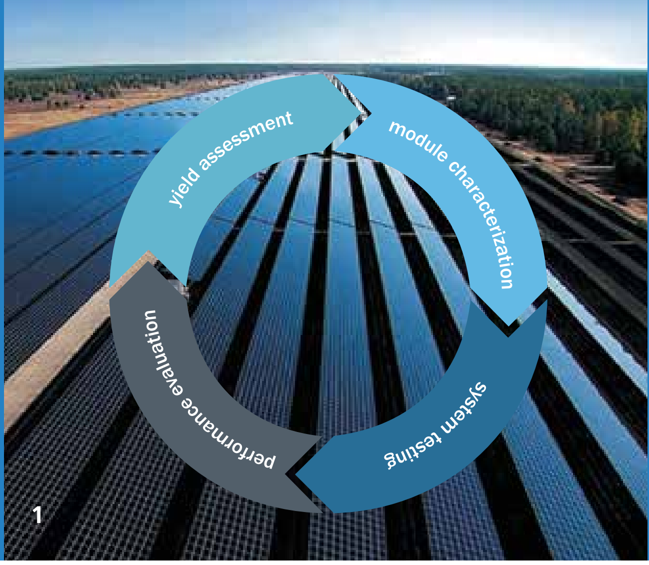
For field measurements, we have a measurement system with up to 96 synchronous measurement channels, which can be used for distributed field measurements, e. g. of a PV park. PV inverters can be tested under real system conditions in our test field in Dürbheim, using the flexibly configurable PV generator with a rated power of 1 MWp and a connection to the 20 kV medium-voltage grid. In addition, a 1.25 MVA transformer with adjustable voltage between 265 and 1120 V is available.

1 *The Megawatt Laboratory allows the interaction of grid-connected power converters with the grid to be characterized with very high accuracy.*

2 *Mobile LVRT test container equipped to investigate the behaviour of large generator systems during short-term grid voltage drops (LVRT). Systems with a maximum apparent power of up to 4.5 MVA can be tested directly on site.*

Services Offered by TestLab Power Electronics

In our testing laboratory we offer the measurement of power generating units such as PV inverters or combined heat and power (CHP) plants according to German (TG3) or other national feed-in regulations, e. g. for Italy, China or Spain. We support our clients in modelling generator units according to German TG4 and in validating these models. Furthermore, highly accurate measurements of the efficiency of power electronic equipment and the total efficiency of PV inverters according to EN 50530 can be made. We carry out customized measurements both in the laboratory and in the field, and are very willing to advise our clients prior to a measurement campaign. We also offer our support for modelling and simulation at scales ranging from individual components of power electronic equipment to complete PV parks. Following the measurements, we evaluate the results according to specified criteria and offer competent advice on options for improvement.



ServiceLab PV Power Plants

Since 1990, Fraunhofer ISE has made an important contribution to quality assurance of PV power plants by the services it provides. With the four phases of the Fraunhofer ISE quality cycle, we offer comprehensive quality assurance of PV power plants from the planning phase to on-going operation.

Our yield assessments form the basis for investors and banks to evaluate the economic viability of a planned PV power plant and provide exact information about the yield to be expected at a given location. When simulating the components, we draw on our expertise in the field and experience of characterizing such components in our laboratories. The internationally unique measurement uncertainty of 1.6 % attained by CalLab PV Modules enables the performance of PV modules to be determined with greatest accuracy.

We offer complete and comprehensive testing of the whole PV system, so that our clients can be sure that their plant really corresponds to the state of the art and delivers the promised power. Its quality can be controlled with on-site analysis that includes visual inspection, thermography, determination of the actual power generated and fault identification.

Once a PV system has commenced operation, we determine the actual Performance Ratio of the power plant and compare the results with the values from the yield assessment. Early detection of sub-optimal operation enables the power plant operators to take the necessary remedial steps as soon as possible.

Boris Farnung, Klaus Kiefer, Frank Neuberger, Harry Wirth

1 *The largest German PV power plant, located in Templin, is subject to comprehensive quality assurance.*

ServiceLab Batteries

Battery Types

We test batteries and battery systems based on lead-acid, NiMH and Li-ion cells, as well as redox-flow and high-temperature batteries and double-layer capacitors. The laboratory with an area of 400 m^2 is equipped with battery testing systems and impedance spectrometers for use either according to the test procedures specified by the relevant standards or in a climatic chamber or a water bath according to clients' specifications.

Long-term tests

We offer long-term tests lasting several months of batteries and battery systems for durability investigations and lifetime analyses.

Automotive sector

We test systems up to a power of 250 kW with currents up to 600 A and voltages up to 1000 V and can control the test systems via a CAN bus.

Stationary sector

Many different home battery packs for private customers are currently entering the market. We test electric storage systems in realistic environments for both grid-connected and off-grid applications, making use of solar simulators and our selection of inverters and charge controllers.

Georg Bopp, Nikolaus Lang, **Stephan Lux**, Stefan Rinne, Matthias Vetter, Günther Ebert

2 *Interior view of ServiceLab Batteries at Fraunhofer ISE.*

ServiceLab Lighting and DC Appliances

Characterization

We carry out accurate measurements of photometric quantities for LED and fluorescent lamps, lights and lighting systems. These include measurement of the luminous flux, the luminous efficacy and the illuminance distribution, and investigations of the operating and long-term performance of the lighting technology under different conditions. For LED light sources and lamps equipped with LEDs, we determine the L70 and L50 lifetimes under various operating conditions and measure the achievable lighting duration (duration of autonomy) for battery-powered lamps. We also determine the electrical properties of electronic controls and electronic ballasts, including the efficiency, operating management performance, overload response and fault management.

Equipment

- software-controlled lighting measurement stand with a photometric integrating sphere of 1.50 m diameter
- software-controlled spectrometer for automated measurement of the light spectral distribution with a photometric integrating sphere of 1.0 m diameter
- luminance camera, luxmeters and long-term test stands
- accurate broadband wattmeters, digital oscilloscopes
- programmable, long-term stable power supplies
- goniophotometer to determine luminosity distribution

Georg Bopp, **Norbert Pfanner**, Günther Ebert

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

ServiceLab Smart Energy

As they become more economically attractive, distributed electricity generators, electric vehicles, heat pumps and electric storage units can be found in many residential buildings. Changes in the subsidy structure are resulting in completely new operating strategies, which are moving away from feeding all the generated electricity into the grid toward on-site consumption with control strategies which help to stabilize the local grid.

The ServiceLab Smart Energy is comprehensively equipped with the types of distributed generators and storage units that will be found in future residential buildings. The laboratory works with powerful simulation tools, which allow model-based "hardware-in-the-loop" operation to evaluate system controllers. This means that any desired dynamic scenario for loads and generation in the building context can be created to evaluate innovative system components such as PV-battery systems and heat pumps.

The infrastructure of the ServiceLab Smart Energy allows system providers to test and evaluate both their individual systems and also complete concepts in a realistic environment, such that business models and control strategies can be investigated. These analyses include e. g. efficiency evaluation and the assessment and development of energy management gateways or local control strategies.

Bernhard Wille-Haußmann, Christof Wittwer, Günther Ebert

2 *Interior view of the ServiceLab Smart Energy.*

ServiceLab Heat Pumps and Chillers

Completion of our new ServiceLab Heat Pumps and Chillers means that we can now offer a broad spectrum of standardized or customized tests for different types of technology (electric, thermal or gas-fuelled) and power classes (up to 100 kW cooling or heating power). The most modern conditioning and measurement technology is available to us. The ServiceLab is equipped to handle natural refrigerants (hydrocarbons, ammonia, CO_2).

Test objects can be measured at temperatures between -25 and 50 °C and air humidity values between 25 and 95 % in a calorimetric double climatic chamber. In addition, the ServiceLab also has several conditioning units for water, brine and air, which enable highly accurate measurements under both stationary and dynamic operating conditions (incl. "hardware-in-the-loop") within a wide range of temperature and air humidity values. Furthermore, component-specific test stands are available for characterization purposes, e. g. compressor or fluid distributor test stands, where advanced measurement technology is used (e. g. particle image velocimetry – PIV; laser shadowgraphs).

Constanze Bongs, Simon Braungardt, **Ivan Malenkovic**, Marek Miara, Thore Oltersdorf, Peter Schossig, Christian Sonner, York Tiedtke, Jeannette Wapler, Hans-Martin Henning

1 *Detail of a test stand to measure components for flammable coolants.*

ServiceLab Phase Change Materials

Phase change materials (PCM), composites, components and systems are tested in the ServiceLab Phase Change Materials according to the criteria of the quality seal, RAL GZ 869. The laboratory is an authorized certification body for this quality seal.

Measurement instruments are also available to determine the following material parameters:

- thermal conductivity and thermal transmittance (U value) of building components and wall constructions
- specific and latent heat storage capacity, nucleation temperature and supercooling by Calvet and heat-flux differential scanning calorimetry (DSC)
- equipment for thermal cycling
- adiabatic test room constructed according to DIN EN 14240 for static and dynamic measurement of heating and cooling systems
- test cells with outdoor surfaces to measure PCM systems
- characterization of heat transfer fluids:
  - density
  - thermal conductivity
  - particle size
  - viscosity
  - stability analysis
- test facilities to characterize heat transfer fluids and emulsions

Stefan Gschwander, **Thomas Haussmann**, Peter Schossig, Hans-Martin Henning

2 *Calvet DSC for thermal characterization of latent-heat storage materials.*

ServiceLab Thermochemical and Porous Materials

The ServiceLab Thermochemical and Porous Materials offers a broad spectrum of analytical methods to characterize porous materials. They are applied to accompany materials development and answer questions concerning surface area, pore structure, porosity, morphology and adsorption characteristics for different gases.

Our facilities include equipment for isothermal gas sorption measurements with various test gases (N_2, CO_2, EtOH, MeOH, H_2O) to determine the specific surface area, pore volume, pore size distribution and the complete adsorption characteristics with volumetric methods.

In addition, thermogravimetric methods are available for H_2O, EtOH and MeOH as the measurement gases, i. e. determination of the adsorbed mass as a function of pressure and temperature along isobars or isotherms. Our range of equipment is rounded out by instruments for macro-pore characterization by mercury intrusion and density determination by helium pycnometry.

Various calorimeters for different size and temperature ranges, as well as two laser-flash systems, are available to determine heat capacity and thermal conductivity. The methods to investigate morphology include optical and laser-scanning microscopy to determine particle shape and size distribution, roughness and homogeneity of surfaces, as well as X-ray powder diffractometry for structural analysis.

Max Baumgartner, **Stefan Henninger**, Philipp Hügenell, Harry Kummer, Gunther Munz, Peter Schossig, Hans-Martin Henning

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

ServiceLab Fuel Cells

We characterize and test membrane fuel cells and systems with an electric power rating of up to 20 kW_{el}.

Our walk-in climatic chamber allows fuel cell stacks and systems to be investigated over the temperature range from -40 °C to +80 °C and relative humidity values between 10 % and 95 %. The high throughput of conditioned air, up to 2000 m^3 per hour, is notable. For investigations under conditions similar to those in systems, we can also control peripheral equipment such as pumps, ventilators and valves. Inhomogeneities in the stack are identified by simultaneous single cell monitoring of the cell voltage and cell impedance spectrum.

Furthermore, we offer long-term tests of peripheral equipment, e. g. with hydrogen input and under extreme climatic conditions. In addition, we have access to an underpressure chamber to simulate altitudes of up to 6000 m. We investigate cell components with respect to their electrochemical stability with a three-electrode configuration and exposure tests.

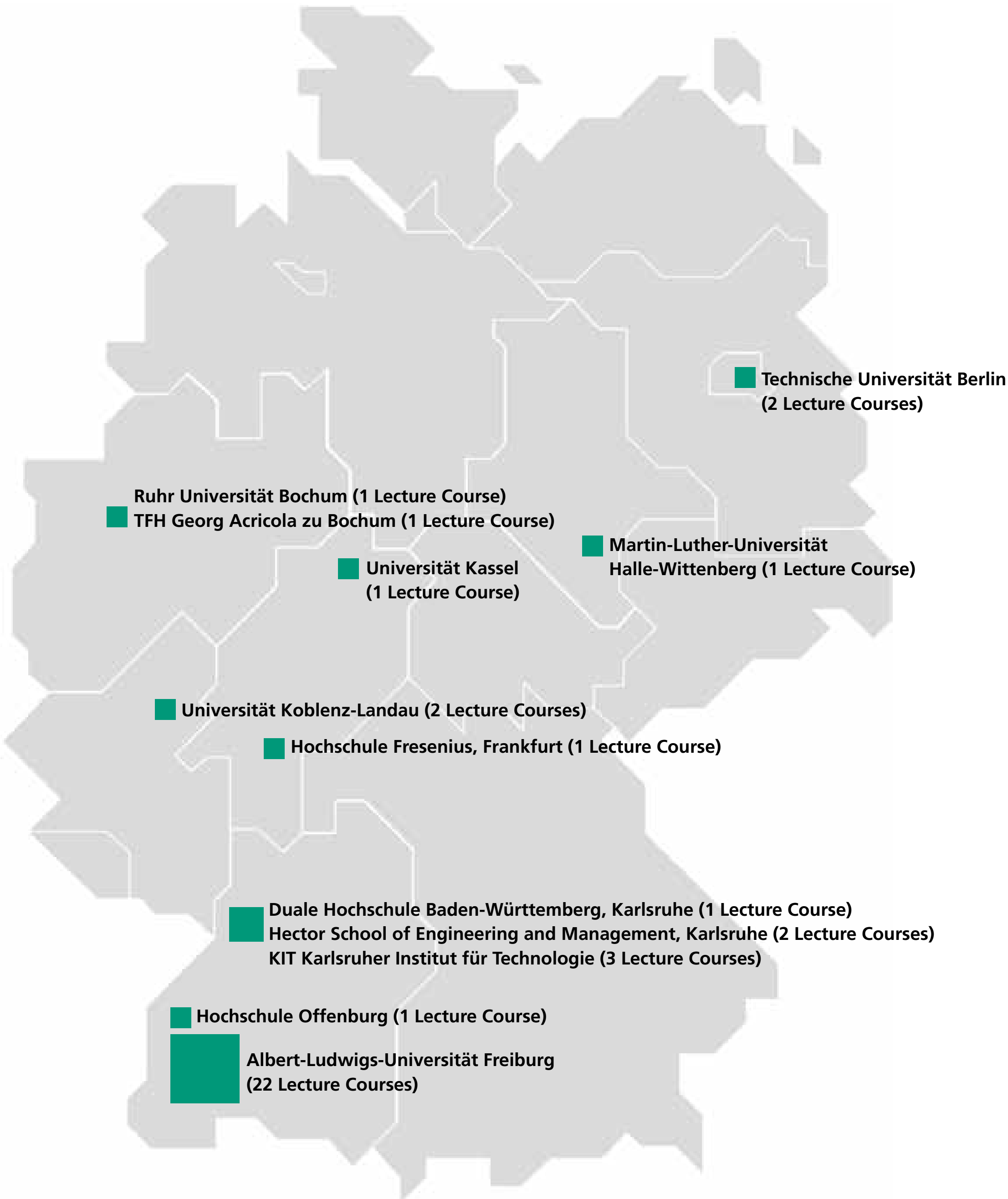
Ulf Groos, Thomas Jungmann, Christopher Hebling

2 *Long-term test of valves at freezing temperatures in a test cell integrated into a climatic chamber.*

APPENDIX

LECTURE COURSES

Fraunhofer ISE has close connections to universities, technical universities and other research institutions. Scientists from Fraunhofer ISE are involved in academic teaching in various cities in Germany. As well as imparting knowledge and practical experience to students, these lecturers also contribute to the high level of expertise at the Institute by their close connections to other academic staff.



A detailed overview of all lecture courses offered by staff of Fraunhofer ISE can be found under: www.ise.fraunhofer.de/lecture-courses

PROFESSORSHIPS AND DOCTORAL THESES

Professorships

Prof. Hans-Martin Henning
Chair for Technical Energy Systems
Faculty of Mechanical Engineering
Karlsruhe Institute of Technology (KIT) , January 2014

Prof. Christof Wittwer
Honorary Professor
Faculty of the Environment and Natural Resources
Albert Ludwig University of Freiburg, July 2014

Doctoral Theses

Helene Ahme
"Spectroscopic Investigations of Transfer and Transport of Charge Carriers in the Donor / Acceptor Network of Organic Solar Cells"
Albert Ludwig University of Freiburg, Freiburg, 2014

Robert Alink
"Wasserhaushalt in PEM-Brennstoffzellen"
(Water balance in PEM fuel cells)
Albert Ludwig University of Freiburg, Freiburg, 2014

Stefanie Essig
"Entwicklung höchsteffizienter GaInP/GaAs/Si-Mehrfachsolarzellen mittels Wafer-Bonding"
(Development of extremely efficient GaInP/GaAs/Si multi-junction solar cells by wafer bonding)
University of Constance, Constance, 2014

Tobias Fellmeth
"Silicium-Solarzellen zur Anwendung in niederkonzentrierenden Systemen – Entwicklung und Charakterisierung"
(Silicon solar cells for application in low-concentration systems – development and characterization)
Albert Ludwig University of Freiburg, Freiburg, 2014

Stefan Fischer
"Upconversion of Sub-Band-Gap Photons for Silicon Solar Cells"
Albert Ludwig University of Freiburg, Freiburg, 2014

Johannes Gutmann
"Photonic Luminescent Solar Concentrators"
Albert Ludwig University of Freiburg, Freiburg, 2014

Barbara Herter
"Photonic Structures for Systems with Silicon Solar Cells and Upconverters"
University of Constance, Constance, 2014

Rene Hönig
"Entwicklung und Mikrostrukturcharakterisierung von Dickschicht-kontakten für hocheffiziente Industriesolarzellen"
(Development and microstructural characterization of thick-film contacts for high-efficiency industrial solar cells)
Albert Ludwig University of Freiburg, Freiburg, 2014

Sabrina Jüchter
"Theoretische und experimentelle Analyse von metallischen Nano-strukturen als Photonenmanagementstrukturen für den Einsatz in Solarzellen"
(Theoretical and experimental analysis of metallic nanostructures as photon management structures for application in solar cells)
Albert Ludwig University of Freiburg, Freiburg, 2014

Martin Keller
"Weiterentwicklung einer Durchlauf-Epitaxieanlage und Implementierung einer turbulenten Gasführung"
(Further development of inline epitaxy equipment and implementation of a turbulent gas supply)
Albert Ludwig University of Freiburg, Freiburg, 2014

Sven Kluska
"Development and Characterization of Laser Chemical Processes for High-Efficiency Silicon Solar Cells"
Albert Ludwig University of Freiburg, Freiburg, 2014

Korbinian Kramer
"Einfluss von Normungs- und Qualitätssicherungsprozessen auf Innovation und Diffusion in der Solarthermiebranche"
(Influence of standardization and quality control processes on innovation and dissemination in the solar thermal sector)
Albert Ludwig University of Freiburg, Freiburg, 2014

Georg Krugel
"Entwicklung und Charakterisierung von gesputterten Schichten zur Passivierung hocheffizienter Siliciumsolarzellen"
(Development and characterization of sputtered films to passivate high-efficiency silicon solar cells)
Albert Ludwig University of Freiburg, Freiburg, 2014

Marek, Miara
"Analytische Methode zur Beurteilung von Wärmepumpen unter Berücksichtigung ökologischer, energetischer und ökonomischer Aspekte"
(Analytical method to evaluate heat pumps, taking ecological, energy-relevant and economic aspects into account)
Technical University of Breslau, Breslau (Wroclaw), Poland, 2014

Bernhard Michl
"Material Limits of Multicrystalline Silicon in Advanced Solar Cell Processing"
Albert Ludwig University of Freiburg, Freiburg, 2014

Anton Neuhäuser
"Untersuchung von Kreisprozessen für die solarthermische Stromerzeugung im kleinen und mittleren Leistungsbereich"
(Investigation of cyclic processes for solar thermal power generation in the low and medium power range)
Technical University of Munich, Munich, 2014

Cornelia Peike
"Degradation Analysis of the Encapsulation Polymer in Photovoltaic Modules by Raman Spectroscopy"
Albert Ludwig University of Freiburg, Freiburg, 2014

Thomas Rachow
"Deposition and Characterisation of Crystalline Silicon"
University of Constance, Constance, 2014

Sebastian Rau
"Hocheffiziente Erzeugung solaren Wasserstoffs durch direkte Verschaltung von III-V-Mehrfachsolarzellen mit PEM-Elektrolysezellen"
(Highly efficient production of solar hydrogen by direct connection of III-V multi-junction solar cells with PEM electrolyser cells)
University of Stuttgart, Stuttgart, 2014

Michael Rauer
"Alloying from Screen-Printed Aluminum Pastes for Silicon Solar Cell Applications"
University of Constance, Constance, 2014

Armin Richter
"Aluminum Oxide for the Surface Passivation of High-Efficiency Silicon Solar Cells – Technology and Advanced Characterization"
University of Constance, Constance, 2014

Philip, Rothhardt
"Co-Diffusion for Bifacial n-type Solar Cells"
Albert Ludwig University of Freiburg, Freiburg, 2014

Sebastian Schiefer
"Durchkontaktierte organische Solarzellen"
(Organic solar cells with via contacts)
Albert Ludwig University of Freiburg, Freiburg, 2014

Kai Schillinger
"Crystalline Silicon Carbide Intermediate Layers for Silicon Thin-Film Solar Cells"
Albert Ludwig University of Freiburg, Freiburg, 2014

Christoph Schwab
"Herstellung und Charakterisierung industrieller oberflächenpassivierter Solarzellen"
(Preparation and characterization of industrial, surface-passivated solar cells)
Albert Ludwig University of Freiburg, Freiburg, 2014

Karl-Anders Weiß
"Charakterisierung und Bewitterungsprüfung von Polymermaterialien für Anwendungen in der Solartechnik"
(Characterization and weathering tests of polymer materials for application in solar technology)
University of Ulm, Ulm, 2014

INTERNATIONAL NETWORK

■

USA
- Fraunhofer Center for Sustainable Energy Systems CSE, Boston (Massachusetts)

Chile
- Center for Solar Energy Technology (CSET), Santiago
- Fraunhofer Chile Research, Santiago

■

Canada, Waterloo
Brazil, Rio de Janeiro
USA, Golden (Colorado)
USA, Atlanta (Georgia)

■

Canada
- University of British Columbia, Vancouver

USA
- CFV Solar Test Laboratory, Albuquerque (New Mexico)
- University of South Carolina, Columbia (South Carolina)
- National Renewable Energy Laboratory NREL, Golden (Colorado)

Brazil
- CTGAS-ER – Centro de Tecnologías do Gás e Energías Renováveis, Lagoa Nova – Natal/RN
- SENAI – DR/RN – Serviço Nacional de Aprendizagem Industrial

A future, global, zero-CO_2 energy supply calls for major effort from all parts of the world. Fraunhofer ISE thus participates actively in an extensive international network, with its own German and international subsidiaries (■), Memoranda of Understanding with universities and research institutions around the world (■) and, last but certainly not least, numerous international guest scientists from universities and research institutes abroad (■), who carry out their research at Fraunhofer ISE, thereby contributing their specific expertise. In addition, Fraunhofer ISE is engaged in various international committees, associations and organizations:
www.ise.fraunhofer.de/en/about-us/organisations

Germany
- Fraunhofer Institute for Solar Energy Systems ISE, Freiburg
- Laboratory and Service Centre Gelsenkirchen LSC, Gelsenkirchen
- Fraunhofer Centre for Silicon Photovoltaics CSP, Halle/Saale
- Technology Centre for Semiconductor Materials THM, Freiberg

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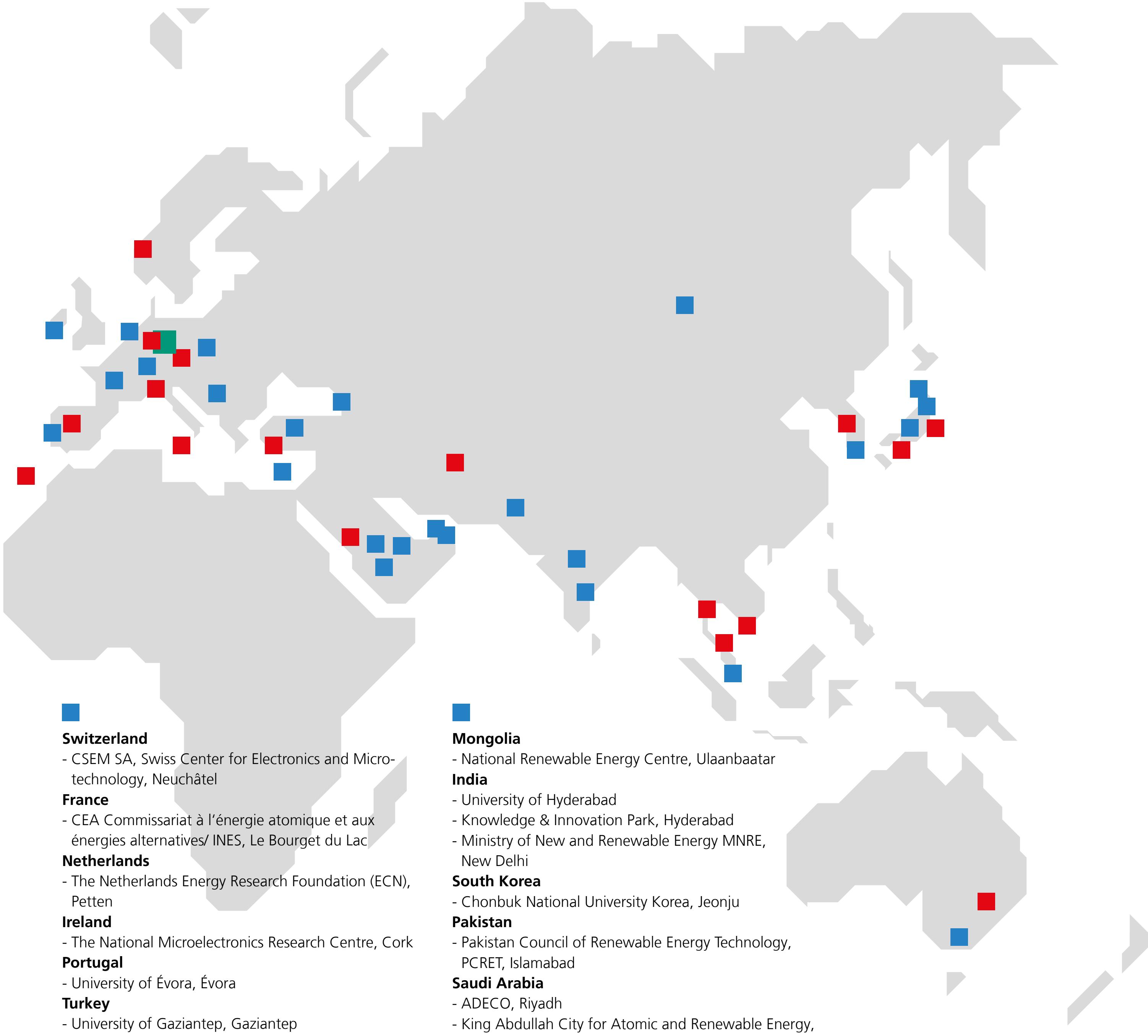
- Fukushima Prefecture
- Inter-University Research Institute for Energy Technology, Ibaraki



Switzerland
- CSEM SA, Swiss Center for Electronics and Micro-technology, Neuchâtel

France
- CEA Commissariat à l'énergie atomique et aux énergies alternatives/ INES, Le Bourget du Lac

Netherlands
- The Netherlands Energy Research Foundation (ECN), Petten

Ireland
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Pakistan
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- Masdar City Project, Abu Dhabi

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Singapore, Singapore
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EVENTS IN 2015 WITH THE PARTICIPATION OF FRAUNHOFER ISE

BAU 2015, International Exhibition for Architecture, Materials and Systems, Munich, Germany, 19.–24.01.2015

The 2015 European Advanced Automotive and Stationary Battery Conference, Mainz, Germany, 26.–29.01.2015

Battery Expo/Fuel Cell Expo, Tokyo, Japan, 25.–27.02.2015

11th SiliconFOREST Workshop, Feldberg-Falkau, Germany, 01.–04.03.2015

30. Symposium Photovoltaische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 04.–06.03.2015

Energy Storage and International Renewable Energy Storage Conference (IRES), Düsseldorf, Germany, 09.–11.03.2015

KONGRESS-Forum ElektroMobilität, Berlin, Germany, 10.–11.03.2015

ISH 2015 (International Bathroom and Heating Exhibition), Frankfurt am Main, Germany, 10–14.03.2015

5th International Conference on Crystalline Silicon Photovoltaics and PV Workshop, Constance, Germany, 23.–25.03.2015

8. Entwicklerforum Akkutechnologien, Battery University, Aschaffenburg, Germany, 24.–26.03.2015

nPV workshop, Constance, Germany, 25.–26.03.2015

7th International Conference on PV Hybrids and Mini-Grids, Bad Hersfeld, Germany, 10.–11.04.2015

11th International Conference on Concentrator Photovoltaics (CPV-11), Aix-les-Bains, France, 13.–15.04.2015

Hanover Trade Fair, Hanover, Germany, 13.–17.04.2015

5. SOPHIA Workshop PV Module Reliability, Loughborough, UK, 16.–17.04.2015

9th SNEC PV POWER EXPO 2014, Shanghai, China, 28.–30.04.2015

25. Symposium Thermische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 06.–08.05.2015

PCIM Europe, Nuremberg, Germany, 19.–21.05.2015

4th Symposium Small PV Applications 2015, Munich, Germany, 08.–09.06.2015

Intersolar Europe, Munich, Germany, 10.–12.06.2015

42nd IEEE Photovoltaic Specialists Conference, New Orleans, USA, 14.–20.06.2015

ACHEMA, Frankfurt am Main, Germany, 15.–19.06.2015

Intersolar North America, San Francisco, USA, 14.–16.07.2015

30th EUPVSEC, Hamburg, Germany, 14.–18.09.2015

IAA, Frankfurt, Germany, 17.-27.09.2015

6th International Solar Air-Conditioning Conference, Rome, Italy, 24.-25.09.2015

World of Energy Solutions 2015 / f-cell 2015, Stuttgart, Germany, 12.–14.10.2015

Sustainability Summit, Freiburg, Germany, 19.–20.10.2015

7. eCarTec, Munich, Germany, 20.–22.10.2015

7th World Conference Photovoltaic Energy Conversion (WCPEC-7), Kyoto, Japan, 24.-28.11.2015

Building Simulation Conference 2015, Hyderabad, India, 07.-09.12.2015