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FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2013/14

Cover:
Microstructured and nanostructured surfaces are developed at Fraunhofer ISE for photon management in optical systems for solar cells, lighting systems, optical sensors or display applications, for example. The fabrication of such surface structures with customised forms and dimensions over large areas is the basis for industrial implementation. Interference lithography is a well established technology at Fraunhofer ISE. Unique is the feasibility of seamlessly structuring areas of up to 1.2 x 1.2 m^2 and the wide variety of possible structures. The architecture and infrastructure of the new laboratory building, which was officially inaugurated in 2013, took the specific requirements of this technology into account. The new measures implemented to improve the process stability mean that even more sophisticated structures can now be produced by interference lithography with even greater reproducibility and accuracy (page 132/133).

FOREWORD

The difficult economic situation for the German photovoltaic sector and social and political uncertainty concerning the energy transformation in Germany strongly influenced the development and strategy of our Institute also in 2013. The enormous global overcapacity in the PV industry – particularly the production capacity for approximately 60 GW in China – was accompanied by a rapidly growing global market of "only" around 35 GW in 2013. The module prices dropped dramatically and overcapacity was reduced by sales at extremely low prices. Many manufacturers could no longer cover costs or remain competitive, as was also evident in Germany. A compounding factor was the state of upheaval in the energy sector. Ongoing discussions on the German Renewable Energy Law and the form which the energy transformation should take have led to tangible caution concerning investments. The result was that renowned German manufacturers withdrew from the photovoltaic market. Several important market players survived only with the help of financing by partners from Asia or the Middle East.

The positive side of the market development is that the favourable prices for solar modules and systems open up new markets for the technology. Thus, the global market is growing rapidly – we anticipate an annual volume clearly exceeding 40 GW in 2014. In the next few years, the gap between overcapacity and global demand will close and orders will increase again. To support the PV sector in Germany, so that it can benefit from the next demand boom, Fraunhofer ISE is participating intensively in the so-called "xGWp" project. This was initiated by a European consortium including leading research institutes, renowned PV suppliers and other industrial and research partners. The goal of the consortium is to establish exemplary European PV manufacturing, in which newest-generation cells and modules can be produced cost-effectively in GW quantities in highly automated factories, so that they can be sold profitably for the current and future market prices. This should create a basis for further success of European PV technology on the global market.

At the same time, the significance not only of photovoltaics but also of other renewable energy topics has increased due to the planned energy transformation in Germany. It is clearly evident that systems approaches encompassing different types of technology have become more important. With its broad and interdisciplinary expertise, Fraunhofer ISE is very well equipped to meet this challenge. Not only do we successfully offer our R&D services for photovoltaic technology but we have been active for decades with research on thermal use of solar energy, storage technologies of different types, energy efficient power electronics, system integration of electricity, heat and gas, energy efficiency of buildings, zero-emission mobility and energy system analysis. In order to make still better use of this multi-facetted competence and resulting synergetic effects, and to tune them to the changing markets and funding structures, Fraunhofer ISE began a fundamental strategic evaluation process in 2013. This allows us to define our position more precisely and focus our resources still better. We will continue this process in 2014.

In 2013, Prof. Hans-Martin Henning and Andreas Palzer publicised a comprehensive model entitled "REMoD-D" for a future German electricity, gas and heat system, assuming major penetration by renewable energy. Detailed modelling of all 8760 hours in a year revealed that a system with renewable energy supplying 70% of the primary energy consumption can guarantee a stable energy supply for costs which are close to those of today's system. By comparison, it would be significantly more expensive to continue with the currently existing system, which is essentially based on fossil fuels. The savings due to the former option would already exceed the required investments by the target year of 2050. Thus, the energy transformation will be financially advantageous for the German economy overall!

Our holistic, systems-based approach is also evident in the "Energy Transformation Index" (ETI), which was developed and presented by Fraunhofer ISE in 2013. This index provides

a completely new instrument to rank the success of different countries in achieving energy transformation. Previously, there had not been any methodical, quantitative approach to measure progress by individual countries and regions toward energy transformation. The index, which was presented for the first time at the Annual Conference of the International Solar Energy Society ISES in November 2013, shows clearly how far the energy transformation has proceeded in different countries around the world. The index is the average of the normalised energy efficiency and the share of renewable energy in primary energy consumption. Energy efficiency is defined here as the quotient of gross domestic product and primary energy consumption. We have defined two dollars per kilowatt-hour as the target value to normalise the energy efficiency; this is about twice the current value for industrial nations today. Of course, normalised efficiency values greater than 100% according to this definition are possible and desirable. With this new approach, we have evaluated 46 countries and the EU average up to now. At present, Germany is ranked equal to Japan and Great Britain in the middle of the field with the 14th position. Thus, according to this scale, the energy transformation in Germany has not progressed as far as is generally assumed. Although this ranking naturally depends strongly on each national starting point, it will be very interesting to pursue the further development of the ETI in each individual country. We will thus cooperate with ISES to publish figures for the ETI regularly in future.

In 2013, Fraunhofer ISE further strengthened its international network by cooperation with new partners. The Institute signed a Memorandum of Understanding with the International Renewable Energy Agency IRENA in Abu Dhabi with the goal of intensifying the existing cooperation. Furthermore, a cooperation agreement with the Indian Ministry for New and Renewable Energy was signed. It focuses on research, demonstration and pilot projects on photovoltaics, hydrogen and thermal use of solar energy. In addition, the Fraunhofer-Gesellschaft and the University of British Columbia UBC in Canada founded a new research alliance. Both parties intend to jointly develop sustainable concepts for energy conversion and supply for the future. Fraunhofer ISE is one of the major participants in this alliance.

Last year, Fraunhofer ISE also excelled in its technological performance. Together with Soitec, CEA-Leti and the Helmholtz Centre in Berlin, we set a new world record for converting sunlight into electricity. The record solar cell is based on a new structure with four sub-cells. After just over three years of research, a new record efficiency value of 44.7% was measured for a concentration of 297 suns. This represents a significant step toward further cost reduction for photovoltaic electricity along the path toward the 50 percent solar cell.

A major highlight of 2013 for us was the official opening of a new laboratory building in Freiburg. With an area of 2400 m^2, it houses facilities under a single roof for our cross-divisional research on thermal solar energy and photovoltaics. We work there on coatings, microstructures and optical and photonic applications to generate heat and electricity. In the new building, materials and processes are developed to coat absorber pipes for solar thermal power stations or produce microstructured surfaces that optimise solar cell surfaces, anti-reflective solar glass or displays. Moreover, equipment is available there to functionalise and enhance surfaces and to analyse surface properties. The characterization and development of concentrator optics is another topic which is pursued in the new laboratory building. On its roof, there is a small outdoor test field for different types of concentrator collectors.

A research team from Fraunhofer ISE developed the energy efficiency concept for the new building and implemented it together with planners, architects and industrial partners.

In addition, the most recent technology developed at Fraunhofer ISE is applied in practice in the new laboratory building. One example is the angle-selective photovoltaic glazing integrated into the spandrel zone of the seminar room. Another is located on the south-west façade, where novel crystalline PV modules have been used to clad the external wall. They are based on innovative solar cell technology with back contacts – implementing the High-Performance Metal Wrap-Through (HIP-MWT) concept that has been developed in-house and patented. The solar cells were produced in a pilot production line in the Photovoltaic Technology Evaluation Center (PV-TEC) of Fraunhofer ISE. The cells are connected with structured cell connectors which were developed and patented by Fraunhofer ISE. The mounting method for the solar cell strings between two glass panes, based on edge-sealed module technology, is also the subject of a Fraunhofer ISE patent.

Thus, the new laboratory building is very important to us for many different reasons. We are very grateful to the German Federal Ministry of Education and Research (BMBF) and the Baden-Württemberg State Ministry of Finances and Economics, which each provided half the necessary funding, for their clear commitment to investment in research and development for the energy transformation and for supporting the work of Fraunhofer ISE. The new building is both a good foundation and an incentive to achieve further breakthroughs in applied research for renewable energy.

Furthermore, our Fraunhofer ISE campus with the new laboratory building is a building block for the National Centre of Excellence for Sustainability, which is currently being planned. It is based on intensive cooperation on the topic of sustainability between the five Fraunhofer Institutes located in Freiburg and the Technical and other Faculties of the University of Freiburg. The five Fraunhofer Institutes will also be involved in creating a new Institute for Sustainable Systems Engineering within the Technical Faculty. The Fraunhofer-Gesellschaft is planning to cooperate with scientific and industrial partners to establish national Centres of Excellence with clear thematic profiles in several German cities. The goal is to achieve even better integration of excellent research and teaching with economic activities in the region and beyond than already exists today.

On 29th November 2013, we were able to celebrate a special birthday, when Prof. Adolf Goetzberger, who founded the Institute more than 30 years ago and who is still active for and at the Institute, turned 85.

Finally, the new calendar year began with a great honour for Fraunhofer ISE, and also for me personally. At the World Future Energy Summit in Abu Dhabi, on behalf of Fraunhofer ISE, I was able to accept the Zayed Future Energy Prize 2014 in the Non-Governmental Organisation (NGO) category from the Crown Prince of Abu Dhabi. The evaluation criteria for awarding this prize with a value of 1.5 million US dollars included our sustainability and our innovation potential.

We express our deep gratitude to our Board of Trustees and scholarship donors, our contact persons in the Ministries on the Federal and State levels and funding bodies – particularly our industrial partners – for the funding and support of our Institute. This trustful cooperation is the foundation for our striving toward a zero-CO_2 global energy supply.

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

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ORGANISATIONAL STRUCTURE

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

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).

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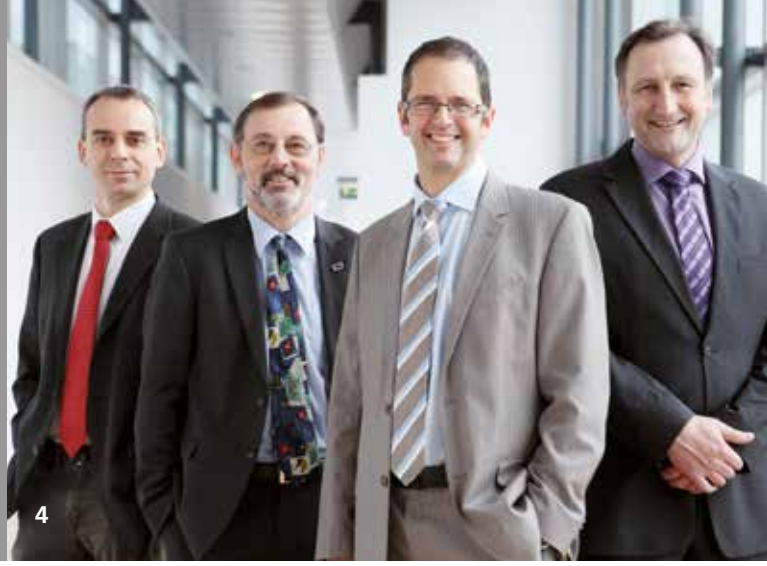

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1 The directors of Fraunhofer ISE (f.l.t.r.): Dr Holger Schroeter, Chief Financial Officer; Prof. Hans-Martin Henning, Deputy Director and Director Division "Thermal Systems and Buildings"; Prof. Eicke R. Weber, Institute Director; Dr Andreas Bett,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

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

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

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THE INSTITUTE IN BRIEF

The Fraunhofer Institute for Solar Energy Systems ISE is committed to promoting energy supply systems which are sustainable, economic, safe and socially just. It creates technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialised, threshold and developing countries. 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 areas of expertise 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 organisation 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 the Fraunhofer-Gesellschaft

- 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), specialises 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 Crystallisation 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 crystallisation processes applying industrial-type equipment, which goes well beyond the current state of the art (page 30).

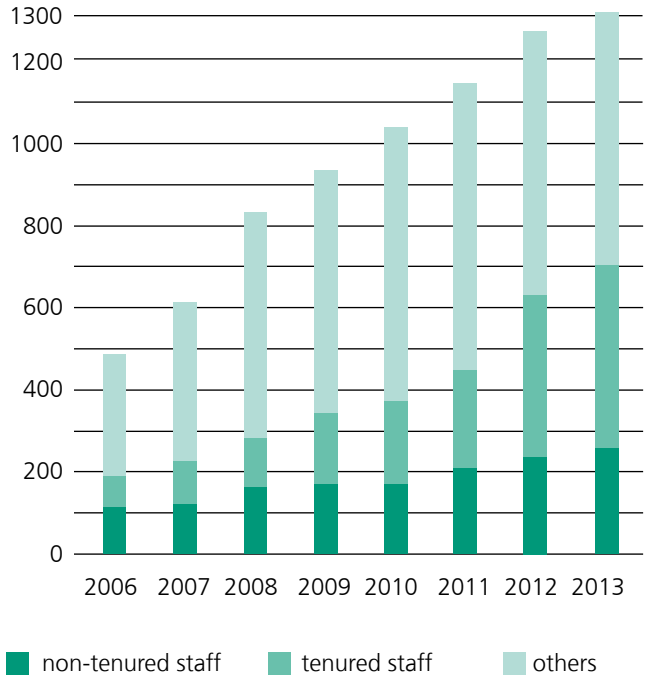
Technology Centre for Semiconductor Materials THM

The Technology Centre for Semiconductor Materials THM in Freiberg, Saxony, is a cooperation between Fraunhofer ISE and the Fraunhofer Institute for Integrated Systems and Device

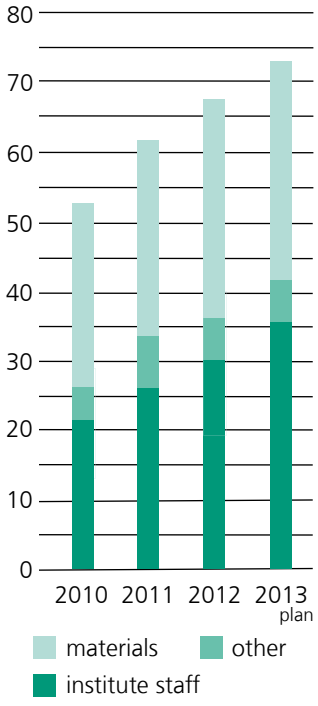
Technology IISB in Erlangen. THM supports companies by research and development on materials preparation and processing of 300 mm silicon, solar silicon and III-V semiconductors. In addition, THM offers services in the fields of analytics, characterization and testing.

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) and the VDE Institute for Testing and Certification, Fraunhofer CSE set up a test facility for PV modules in 2010. The facility, called the CFV Solar Test Laboratory, is located in Albuquerque, New Mexico.

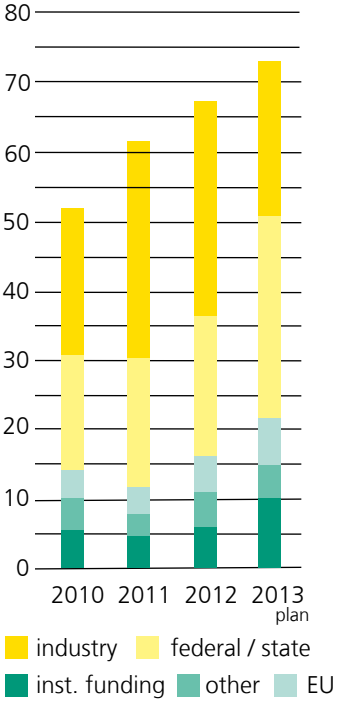
Personnel



Expenditure million €



Income million €



On 31st December 2013, a total of 1301 staff members were employed at Fraunhofer ISE. Included in this total are 165 doctoral candidates, 135 Diploma / Masters students, 44 trainees and 291 scientific assistants as well as 114 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 the operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. In 2013 our operational budget totalled 73.1 million euro. In addition to the expenditure documented in the graph, the Institute made investments of 13.3 million euro in 2013 (not including investments for building construction and the economic stimulus programme).

NEW EXTERNAL PRESENTATION IN TWELVE BUSINESS AREAS

The broadly based research portfolio applying a systems approach, which has distinguished Fraunhofer ISE since its foundation, has proven its sustainable value, particularly now that the Germany energy transformation is becoming increasingly important. Subjects which have been investigated at Fraunhofer ISE over many years by interaction with industry and in publicly commissioned research projects are now demanded and supported even more strongly due to the political decision to implement the energy transformation. Aiming to specifically address national and international clients and project partners from industry and public funding agencies, as well as politicians, the general public, the media and scientific partners, the Institute has now reorganised its external presentation. For example, research on storage technologies, grids, power electronics, mobility and systems analysis is now more clearly visible among the Institute's twelve business areas. In addition, a new access route via areas of expertise facilitates the identification of services in R&D, testing and certification for interested enquirers, not only those from the energy sector.

Core research at Fraunhofer ISE focuses on topics within the fields of **Energy Efficiency, Energy Conversion, Energy Distribution and Energy Storage**. The twelve business areas of Fraunhofer ISE, which are presented in the following paragraphs, are the display windows on its R&D accomplishments.

Energy Efficient Buildings are of key importance within the overall context of energy efficiency. More than 40% of the German end energy demand is consumed within the building sector. Fraunhofer ISE works on solutions for residential and non-residential buildings, for newly built and the existing building stock – ranging from materials research up to energy supply concepts. Increasingly, the approaches extend beyond individual buildings to cover urban districts and even whole cities (page 16 ff.).

Within **Silicon Photovoltaics**, the goal is to cooperate with industry in developing new products up to commercial maturity and to further reduce the levellised costs of electricity for this major PV technology by lowering production costs and increasing efficiency values. A central concern is to make the PV industry in Germany and Europe more competitive. Fraunhofer ISE conducts research on the entire value chain for silicon photovoltaics, from crystallisation to module technology (page 24 ff.).

III-V and Concentrator Photovoltaics plays an important role for high-efficiency photovoltaic power plants and space applications. Highly efficient and lightweight multi-junction solar cells of III-V semiconductors are used in satellites. These multi-junction solar cells, but also special silicon solar cells, are used in concentrator power plants in sunny regions and achieve lower levellised costs of electricity there (page 46 ff.).

Other PV technologies are developed in the business area **Dye, Organic and Novel Solar Cells**. Improved photon management and cost reduction by the application of new materials and manufacturing processes are central topics. Dye solar modules are intended for architectural applications whereas organic solar cells open up completely new application areas due to their flexibility (page 54 ff.).

The focus with regard to **Photovoltaic Modules and Power Plants** is on efficiency and reliability. Here, we develop module technology for new generations of solar cells and test innovative materials. Their service life is investigated by analysing environmental factors and degradation, as well as comprehensive testing. We characterize modules of different PV technologies with the highest accuracy, and – at the end of the chain – we analyse and optimise the yield of PV power plants (page 62 ff.).

1 / 2 *Main building and new laboratory building of Fraunhofer ISE in Freiburg, Germany.*

Solar heat plays a central role in the transformation of our energy systems. **Solar Thermal Technology** encompasses the entire market from low-temperature to high-temperature applications, from domestic hot water and solar space heating systems, through cooling and refrigeration, to component and system development for large solar thermal power plants. Solar process heat for industrial applications and decentralised water purification are also included among the central research topics (page 74 ff.).

As the share of grid electricity from renewable energy resources increases, hydrogen is becoming more and more important as an energy storage medium and fuel. In the business area for **Hydrogen and Fuel Cell Technology**, we are conducting research on innovative technology to generate hydrogen by electrolysis of water and from biogenic fuels, as well as efficient conversion of hydrogen into electricity and heat by PEM fuel cells. Based on our many years of experience in chemical engineering, process technology and catalysis, we have also expanded our activities to include non-energy (chemical) applications and low-emission combustion (page 88 ff.).

System Integration and Grids – Electricity, Heat, Gas encompasses the cross-linking and integration of different energy systems with modern grid infrastructure. "Smart Grids", intelligent operation management of decentralised generators and cross-sector storage in heating, electricity and gas networks are central topics. The focus is on decentralised and regionally connected energy systems within the context of transformation of the entire German energy system. Research on municipal concepts is concentrating on "Smart Energy Cities", which are the subject of the Fraunhofer "Morgenstadt" initiative (City of the Future) (page 94 ff.).

Power electronic components and systems are vitally important for our future energy system but also for applications in electromobility or aviation. We offer a broad spectrum of R&D services up to series development for **Energy Efficient Power Electronics**. In addition to increasing the energy efficiency and integrating new functions, we focus on decreasing the volume and mass of components and reducing the manufacturing costs for inverters, rectifiers, converters and control systems (page 102 ff.).

The business area for **Zero-Emission Mobility** includes research services to provide mechanical energy and infrastructure for sustainable mobility within the context of the German energy transformation. Purely battery-powered vehicles and fuel cell vehicles are both subjects of research. The Institute characterizes and develops systems and components related to the drive unit and the interface between vehicles and fuelling infrastructure. It operates a publicly accessible hydrogen filling station as a research platform (page 108 ff.).

Storage technology for different forms of energy such as electricity and heat has been a subject of research at Fraunhofer ISE since its inception. Today, R&D work on **Storage Technologies** ranges from lithium-ion and redox-flow batteries, through electrolysis and hydrogen technology, up to storage units for solar thermal power plants and phase-change materials in intelligent building materials and cold storage (page 114 ff.).

The globally increasing share of energy supplied from renewable sources raises new questions for research. **Energy Systems Analysis** at Fraunhofer ISE is not restricted to cost and technological analysis but also deliberately addresses questions of cost-effective utilisation of renewable energy resources, optimised combination of different technologies within the energy system and further development of the energy system as a whole (page 122 ff.).

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1 *Zayed Future Energy Prize 2014 for Fraunhofer ISE: Prof. Eicke R. Weber (left), Sheikh Mohammed Bin Zayed Al Nahyan (right).*

PRIZES AND AWARDS

Dirk Kranzer
3rd Poster Prize for "Trafolosen einphasigen Modulwechselrichter mit SiC-Transistoren", Ostbayerisches Technologie-Transfer-Institut e. V. (OTTI) at the 28. Symposium Photovoltaische Solarenergie, 6.–8.3.2013, Bad Staffelstein, Germany

Dr Olivier Stalter, Florian Reiners, Michael Eberlin, Sebastian Franz with Frank Seybold from KACO new energy GmbH
SEMIKRON Innovation Prize for "Neue Leistungselektronik für die vollständige Dorfstromversorgung in Entwicklungs- und Schwellenländern", SEMIKRON-Stiftung at PCIM Europe 2013, June 10, 2013, Nuremberg, Germany

Prof. Eicke R. Weber
Einstein Award from SolarWorld for promotion of European solar research, SolarWorld AG at Intersolar Europe 2013, June 20, 2013, Munich, Germany

Dr Pierre Saint-Cast
Junior Einstein Award from SolarWorld for development of a novel passivation method for silicon solar cells, SolarWorld AG at Intersolar Europe 2013, June 20, 2013, Munich, Germany

Stefan Fischer
Best Student Presentation Award in the category "Area 1 – Fundamentals and New Concepts" for "Upconversion of Silicon Solar Cell Devices for Efficient Utilization of Sub-band-gap Photons under Solar Radiation", IEEE Photovoltaic Specialists Conference (PVSC), June 21, 2013, Tampa, Florida, USA

Dr Bruno Bueno
Best Paper Award 2013 for "The Urban Weather Generator", Journal of Building Performance Simulation, August 27, 2013

Subarna Sapkota
Nepalese Medal of Education (Nepal Vidhya Bhusan Padak "Kha") for the best final mark in the Master's course on "Renewable Energy Management" at the University of Freiburg, Nepalese National Education Day, September 8, 2013, Kathmandu, Nepal

Florian Schindler
Poster Award for "Material Limitations due to Crucible Impurities in Multicrystalline Silicon for High Efficiency Solar Cells«, 28th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC), 30.9.–4.10.2013, Paris, France

Marek Miara
Award for promotion of the development of heat pump technology in Poland, Polish Heat Pump Association at II. Heat Pump Congress PORT PC, 16.–17.10.2013, Warsaw, Poland

Dr Martin Schubert
Ulrich Gösele Young Scientist Award 2013 for research on the measurement, simulation and origin of impurities in multicrystalline silicon, Crystalline Silicon Solar Cells Conference (CSSC-7), October 10, 2013, Fukuoka, Japan

Dr Simon Schwunk
Prize for excellent doctoral thesis on "Partikelfilter zur Ladezustands- und Alterungsbestimmung bei Lithium-Ionen-Batterien auf Basis von Metalloxiden und Phosphorolivinen", FernUniversität Hagen, November 15, 2013

Fraunhofer Institute for Solar Energiesystems ISE
Zayed Future Energy Prize 2014 in the Non-Governmental Organization (NGO) category, worth 1.5 million US dollars, presented by Sheikh Mohammed Bin Zayed Al Nahyan, Crown Prince of Abu Dhabi, World Future Energy Summit, January 20, 2014, Abu Dhabi, United Arab Emirates

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The Board of Trustees assesses the research projects and advises the Institute Directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the work program of Fraunhofer ISE (Status: 31st December 2013).

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 industrialised countries. The largest fraction of the energy is used to create indoor comfort – heating, cooling, ventilating, dehumidifying, rehumidifying – and for domestic hot water and artificial lighting. Mainly fossil fuels are used for this, predominantly natural gas and heating oil; their combustion leads to emission of greenhouse gases. The building sector thus has a major role to play in reaching the targets for climate protection.

The German Federal Government has set itself the goal of achieving a CO_2-neutral building stock by 2050. In the European Union, all new buildings from 2021 onward – new public buildings already from 2019 – must be nearly zero energy buildings; this demands that the average annual energy balance be almost zero. Reduction of the building energy demand and meeting the remaining demand by renewable energy are thus key requirements.

Energy efficient buildings represent a central area of activity at Fraunhofer ISE. Our work 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. In addition, our research and development work increasingly addresses solutions which extend beyond the individual building, for example local heating networks for urban neighbourhoods or measures for whole cities based on detailed simulation to support the concrete implementation of climate protection concepts.

The building envelope is the most important starting point to reduce energy consumption. Our work ranges from materials research for opaque and transparent building components, through the development of façade concepts, to quality control as support for innovative building concepts. In addition to optimising the use of daylight combined with high visual comfort, the integration of active components to convert solar energy into heat and electricity is playing an increasingly important role.

Building plant technology offers great potential to reduce the primary energy consumption and integrate renewable energy sources. We are working on all relevant technologies to supply heating, cooling and electricity in buildings. This includes not only storage units for renewable energy and load management but also the integration of ambient heat sources and sinks, and optimised indoor heat supply systems. One focus of our work is electric and gas-driven heat pumps, which represent a key technology for an energy system based on renewable energy. Broadly based monitoring of technical systems and entire buildings is an important instrument for quality control and to identify potential for optimisation. We have gained extensive experience in the implementation of monitoring campaigns and developed powerful tools in measurement technology and standardised analysis, visualisation and error identification.

Buildings and their technological equipment are complex systems. Modern operation management concepts thus play a central role in ensuring maximal comfort for minimal energy consumption in practical operation. A further aspect is that in future, buildings and building technology will have to fulfil more stringent requirements with respect to services for the external electricity grid. We are developing both software solutions and hardware components which will enable flexible energy management for grid integration.

FURTHER INFORMATION

Staff	113
Staff: Full-time equivalent	97
Journal articles and contributions to books	38
Lectures and conference papers	56

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New laboratory building at Fraunhofer ISE: Seminar room with building-integrated photovoltaics (BIPV) – semi-transparent PV modules with angle-selective transmission (PV Shade®).

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LOWEX ENERGY CONCEPT WITH INTEGRATED COLD WATER STORAGE

A low-exergy heating and cooling concept was developed for the new laboratory building at Fraunhofer ISE. A large underground cold water tank with a volume of 500 m³ was integrated into the building in order to meet the high process cooling demand for laboratory and production equipment, compensate for load fluctuations and thus ensure a continuous supply. The short-term storage of cold water reduces the required refrigeration power, takes advantage of natural cooling by the outdoor air and allows the chiller to be operated economically and efficiently. To achieve this, problems related to building science and plant technology had to be solved.

Clemens Faller, Sebastian Herkel, **Doreen Kalz**, Nicolas Réhault, Martin Sonntag, Alexander Urbanz, Hans-Martin Henning

The energy supply concept is based on a highly efficient heat pump with magnetically supported turbo-compressors, which simultaneously provides heating and cooling energy and makes use of waste process heat. The heat pump is combined with a building-integrated, stratified cold water tank which fulfils a double function in the heating and cooling supply concept. During heating operation, it functions as a heat source for the heat pump. During cooling operation, it serves to store the cooled water and creates a back-up cooling reservoir for the sensitive process technology in the laboratory building. The tank is primarily cooled by outdoor air and the earth and groundwater located below the tank. The cooling demand generally drops during the night, so the available cooling power from the chiller or the heat exchanger is then used to regenerate the tank. The cold water reserves can then be used, for example, the next day to meet peak loads and thus flatten load peaks in the grid. This flexible operation mode and the modern building concept allow the primary energy demand to be reduced appreciably.

1 *Underground, building-integrated, stratified cold water tank during the building phase.*
2 *Laboratory building at Fraunhofer ISE. Its heating and cooling system applies a low-exergy concept.*

The function of the entire system strongly depends on thermally stratified operation within the tank. As the difference in density for water in the temperature range from 16 to 22 °C is only slight, the charging and discharging facilities were designed very carefully. Dedicated models were developed in the Department for Technical Thermodynamics at the TU Chemnitz which include the concept of radial diffusors that allow charging and discharging within one layer without causing turbulence.

To allow analysis of the energy concept and the performance of the equipment, it is being monitored on a long-term basis.

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

http://lowexbestand.ise.fraunhofer.de

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BUILDING OPERATION INTERACTING WITH THE ELECTRICITY GRID

A major challenge posed by the national energy transformation in Germany is the transition from a currently centralised system to an electric power system which is at least partly decentralised and includes renewable energy sources. The increasing input from fluctuating renewable energy sources into the electricity grid leads to a growing strain on the power grid, which requires efficient load management of the electricity supply and demand. Against this background, we are analysing how buildings behave as controllable energy consumers and thermal storage units in a future, intelligent electricity grid and how they can contribute to grid stability.

1 *Solar estate in Freiburg.*

2 *Storage and distribution of cooling water.*

Sebastian Herkel, **Doreen Kalz**, Konstantin Klein, Andreas Palzer, Martin Sonntag, Simon Winiger, Hans-Martin Henning

A reduced energy consumption in buildings will be achieved essentially by building measures and efficient technology. As the proportion of energy from regenerative sources continually increases, the building of the future must additionally be adapted to the needs of electricity generation which is dominated by renewable sources. The focus is thus on the entire energy system including all generator units. We are developing and testing adapted control and operation management concepts, which enable greater local load management, by designing the operation of electric heat pumps and chillers to be grid-compatible. To assess the interaction between buildings and the electricity grid, we have investigated various grid-related quantities with respect to their patterns over time, fluctuation range and annual and seasonal features. This revealed that the operation of electric heat pumps for heating can be optimised according to the EEX price and the residual load in the supply grid. In the cooling case, optimised operation of chillers during periods with a high proportion of renewably generated electricity in the grid can reduce the demand for primary energy, in particular.

Beyond these aspects, we also determine how load shifts can be implemented by technical (water) storage units in the building and the thermal mass of the building structure. In current work, we have demonstrated that the presently existing systems in non-residential buildings are clearly too small to allow sufficient shifting of the operation schedule during the heating period. Ongoing work is addressing the optimal dimensioning of technical storage units and their integration into buildings, as well as the efficient activation of the thermal building mass to achieve load-shifting.

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

www.netzreaktivegebaeude.de

FIELD MEASUREMENTS OF LARGE HEAT PUMPS

Analyses of the composition of a future, complete German energy system that is designed to achieve minimal total costs show that electric heat pumps will play a central role in supplying heat (page 127). In particular, heat pumps in the higher power range for office and light industrial buildings offer great potential to shift loads by efficient generation and intermediate storage of heat and cooling energy by coordinated interaction with the grid, thus contributing to grid stability. On the basis of measurement campaigns over several years, we are analysing the energy and efficiency performance of large heat pump systems in the thermal power range from 40 to 150 kW_{therm}.

Sebastian Herkel, **Doreen Kalz**, Martin Sonntag, Simon Winiger, Hans-Martin Henning

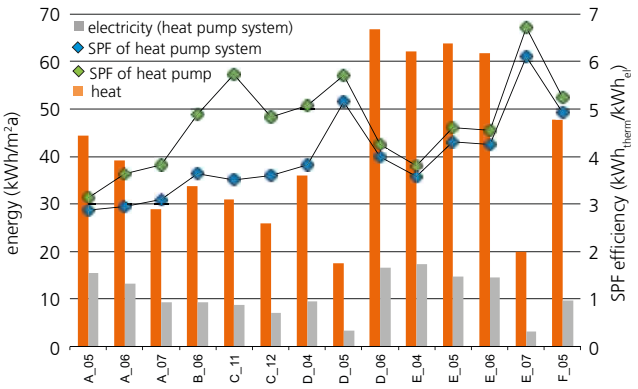
Low-energy buildings with a reduced power and energy demand for heating and cooling allow efficient application of natural ambient heat sources and sinks in combination with heat pumps. In winter, the naturally existing temperature level of the ambient energy is slightly raised by a heat pump, also an economically favourable option. In summer, the earth or groundwater is used directly as a natural ambient heat sink for free cooling of the building. If the building and its usage require more cooling power, air-conditioning can be provided energy-efficiently by a reversible heat pump.

For the heat pump systems in the investigated buildings (heat pump with a compressor and primary pump), seasonal performance factors (SPF) of 3 to 6.1 kWh_{therm}/kWh_{el} (earth) and 3.0 kWh_{therm}/kWh_{el} (ground water) were achieved. Both the primary pump and also the inlet temperature of the secondary transfer system have a decisive influence on the efficiency and seasonal performance factors of the heat pump. The usage of ground-coupled, reversible heat pumps to provide cooling energy represents an efficient and sustainable concept for cooling buildings. Here also, the relatively high inlet temperatures for cooling of 16 to 20 °C lead to high energy efficiency. Based on the monitored data, seasonal performance factors of 4.8 to 5.8 kWh_{therm}/kWh_{el} were demonstrated in projects.

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

www.netzreaktivegebaeude.de

1 *Reversible heat pump with turbo-compressor technology.*



2 *Results of analysing monitored data from large heat pump systems in non-residential buildings: heat provided, electricity consumption of the heat pump systems, seasonal performance factor (SPF) of heat pump (compressor only) and SPF of heat pump system (heat pump and primary loop).*

MODEL-BASED QUALITY CONTROL OF BUILDING OPERATION

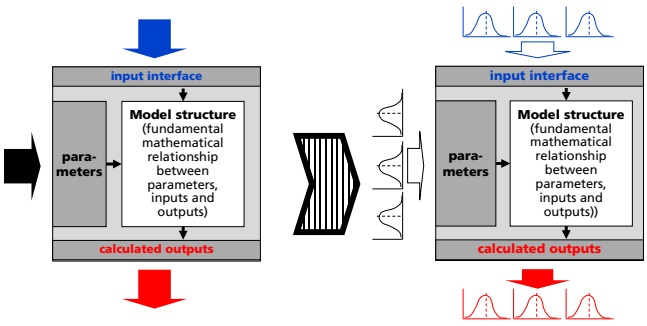
ModQS

Quality in a building technology supply task is characterized by high comfort for the building users combined with minimal energy consumption and thus minimal related costs. Within the project entitled "ModQS – Model-Based Quality Control of Building Operation", the aim was to apply this principle to the heating technology for existing non-residential buildings based on a systematic approach. Energy saving potential was identified by applying model-based fault detection, fault diagnostics and optimisation procedures. Our work demonstrated that the energy saving potential is between 5 and 30%, without significant changes to the plant technology.

Gesa Böhme, Sebastian Burhenne, Sebastian Herkel, Thorsten Müller, Felix Ohr, **Nicolas Réhault**, Tim Rist, Sebastian Zehnle, Hans-Martin Henning

1 *Regional police headquarters in Mettmann, Germany. A modern building with a large window area and a thermally activated building system (TABS) for heat exchange. This type of building presents a major challenge for control technology. For instance, high room temperatures can occur in the transitional seasons if the TABS is charged for heating purposes and large solar gains occur simultaneously.*

2 *District government building in Düsseldorf, Germany. The preparation of simulation models for older buildings is made more difficult by the lack of data to describe the thermal behaviour of the building. Simplified building models, which are calibrated on the basis of measured data, can provide a solution.*

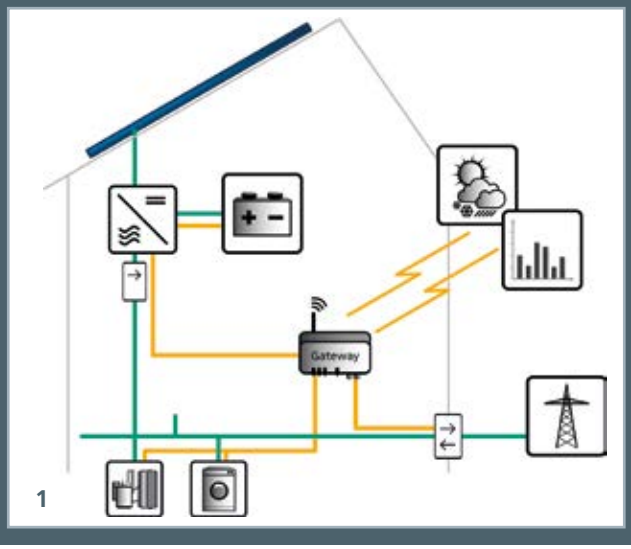


3 *Procedure for simulation or optimisation under uncertain boundary conditions. Some or all parameters and inputs are described by probability distributions. The result is a probability distribution for the outputs, which allows a concept to be evaluated.*

The operation of existing buildings is often sub-optimal and subject to error. This is due to the lack of systematic methods for data acquisition, data processing, fault detection, fault diagnosis and optimisation, which can take account of the interaction between different sub-systems within a complex building plant structure and uncertain boundary conditions (Fig. 3). In the "ModQS project", model-based methods are developed for building energy management, which are intended to detect errors automatically and indicate potential for optimising operation under uncertain boundary conditions.

The project is supported by the German Federal Ministry of Economics and Energy (BMWi) within the "EnOB" and "EnBOP" programmes.

www.modqs.de



1

INNOVATIVE ENERGY MANAGEMENT SYSTEMS FOR BUILDINGS IN A SMART GRID

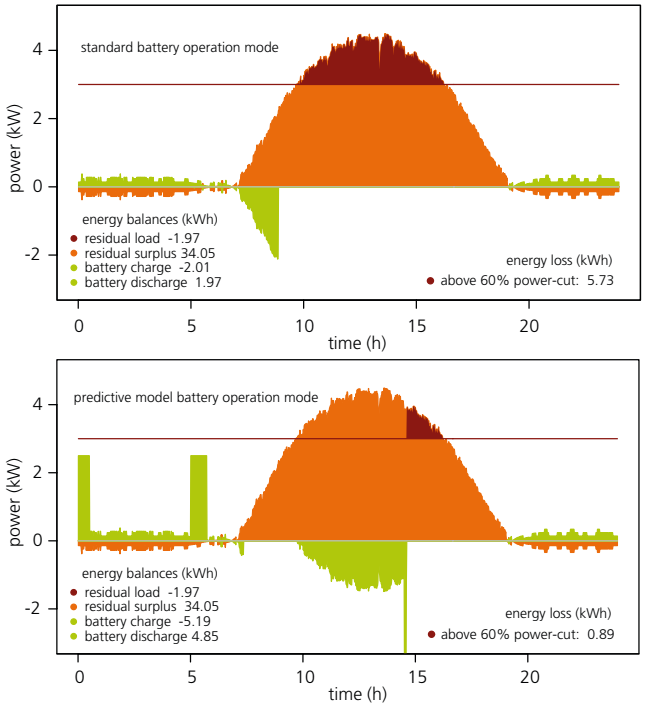
In future, decentralised electricity generators will have to meet more stringent requirements for grid-integrated operation and conform to market demands. In addition, local optimisation will play an important role. These tasks are carried out by energy management systems, which act as a key interface connecting local plants and higher-level systems. At Fraunhofer ISE, we are working on open-source energy management platforms, driver interfaces, data models and predictive optimisation algorithms. One current example is the grid-friendly operation mode of a PV battery system to reduce PV feed-in power around midday.

Felix Braam, Stefan Feuerhahn, **Robert Kohrs**, Christof Wittwer, Michael Zillgith, Günther Ebert

Commercially available PV battery systems are intended to maximise self-consumption. The control parameter used is the power at the building connection point. Grid-friendly operation demands a more complex control system which includes prediction of local generation and consumption, battery charging predominantly during peak power generation periods and provision of corresponding battery capacity. The energy management system, which is centrally integrated into the household grid, is responsible for data acquisition and processing, as well as optimising the energy flows.

In the "Heiphoss" project, we are developing corresponding predictive model algorithms. The run-time environment of the energy management gateway is provided by the "OpenMUC" software framework. "OpenMUC" has been developed at Fraunhofer ISE for several years as an open-source system. It now offers many system interfaces, including IEC 61850, and has already been successfully used in different projects. The technical requirements on an energy management system are: It must be interoperable, flexible under changing boundary

1 *Smart Home concept with a central energy management system.*

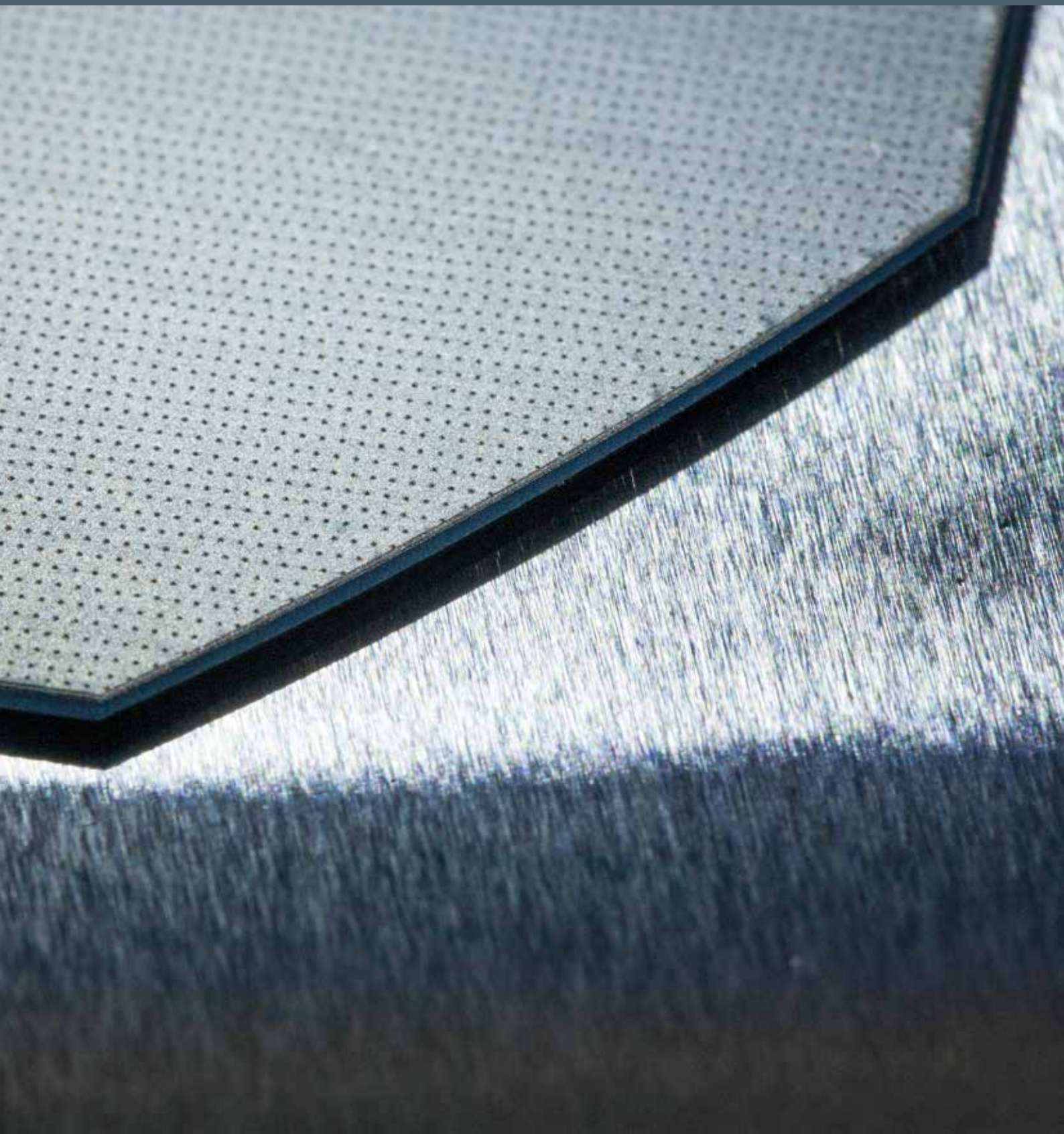


2 *Generation and load data for a typical private building. Prediction-based algorithms have been developed to buffer the power peaks.*

conditions, secure and energy-efficient. In the "Heiphoss" project, a prototype of the new energy management system will be implemented in private buildings and evaluated in 2014 in a field trial. In the "OGEMA 2.0" project, we are investigating and developing further-reaching approaches for energy management systems such as security concepts for several users and abstract data models.

Both projects are supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

SILICON PHOTOVOLTAICS



Around 85% of 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 goal 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 pre-requisite for substantial cost reduction in silicon photovoltaics. Among the various solar cell concepts that currently exist, we are focussing particularly on back-contacted cells and structures for n-type silicon. ETAlab® is equipped with excellent processing infrastructure in a clean-room laboratory with a floor area of 500 m^2. It has allowed us to set several international records for efficiency. In addition, further laboratory area of 900 m^2 is available for us to develop effective surface passivation methods, novel 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 m^2, we can produce both solar cells with screen-printed contacts, as are common in industry, and also solar cells with high-quality surface passivation on a pilot scale, i.e. with a throughput of more than 100 wafers per hour. For the various types of processing technology, both flexible, semi-automatic equipment and high-rate, fully automatic systems for process development are available. All material and processing data are stored in a central data bank, guaranteeing that our high quality specifications are met, which makes them particularly suitable for analysing new materials. Our activities range from development of new concepts at the pilot stage, through evaluation of new technology, to transfer to the production lines of our cooperation partners.

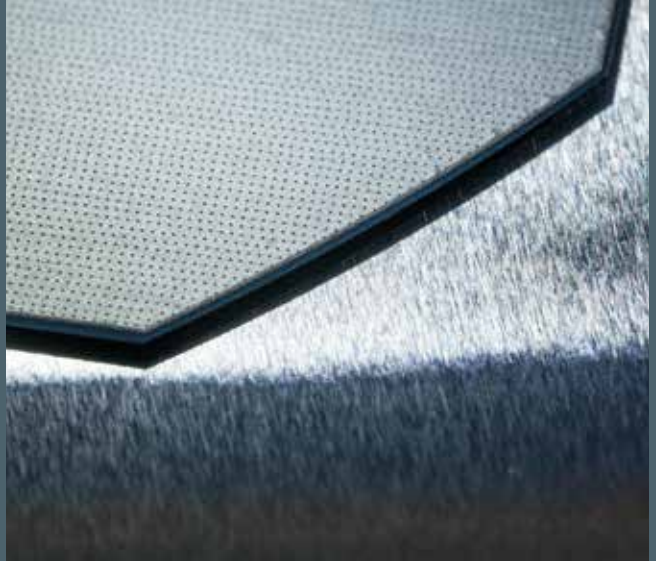
For all of the technological foci mentioned above, our excellent characterization and simulation pool provides the foundation for effective and scientifically based development. We are playing a leading role in the development of new characterization procedures such as the imaging photoluminescence method to analyse silicon material and cells. The Photovoltaic Module Technology Centre MTC at Fraunhofer ISE allows new cells and materials to be processed in industrially relevant quantities and formats. Processing steps and systems technology for module production are developed up to the preliminary stage of mass production.

Our activities on silicon material and solar cells in Freiburg are complemented by the Fraunhofer ISE Laboratory and Service Centre in Gelsenkirchen (page 10).

FURTHER INFORMATION

Staff	364
Staff: Full-time equivalent	282
Journal articles and contributions to books	82
Lectures and conference papers	96

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



Crystal silicon solar cell with its aluminium foil electrode.

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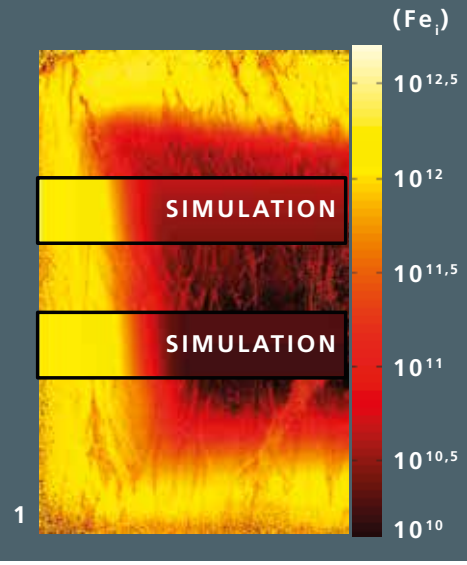


DIFFUSION OF IMPURITIES INTO MC-SILICON BLOCKS

Even when extremely pure feedstock has been used, the electronic material quality in directionally solidified silicon is limited by impurities. The introduction of impurities during the crystallization process is the main reason that the material quality in the centre of the block is reduced and the block cap, base and a broad edge zone cannot be processed into wafers. The main mechanisms for the material quality reduction were determined quantitatively by exact characterization and simulation of the contamination process. This enables specific technological improvements to be made to reduce contamination of the silicon block.

Alireza Abdollahinia, Wolfram Kwapil, Stephan Riepe, Florian Schindler, Claudia Schmid, **Jonas Schön**, Martin C. Schubert, Wilhelm Warta, Stefan Glunz

For the project, boron-doped silicon blocks were crystallized with crucibles and crucible coatings of different purity, and the spatial distribution of the impurity concentration and specific defects was measured. Iron proved to be the impurity which is decisive in limiting the charge carrier lifetime.

Diffusion into the silicon melt and solid can now be described during the entire crystallization process by applying a model developed at Fraunhofer ISE for precipitation and diffusion in silicon, the crucible and the coating. The simulated and measured distribution of iron shows very good agreement for different blocks (Fig. 1). The potential of higher-purity crucible materials and process optimisation can be evaluated by exact analysis: Usage of an extremely pure crucible particularly reduces the extent of the peripheral diffusion zones which cannot be used for solar cell production. By contrast, the limited purity of available coatings restricts the potential for improvement in zones far from the edges. In addition, the simulations allow the results to be transferred to large, industrial crucible systems.

1 *Measurement of the dissolved iron concentration (Fe_i in cm^{-3}) in a vertical slice of the block produced in an extremely pure crucible. The very good agreement with the simulations can be seen in the superimposed images.*

2 *Efficiency-Limiting Bulk Recombination Analysis (ELBA) of PERC cells from standard material (SQ) and from material which was produced in extremely pure crucibles (HR). In particular, cells from standard material are limited by diffusion of impurities from the crucible system into the block.*

Measurements of the charge carrier lifetime and iron concentration in wafers, some of them processed, were used to determine the specific efficiency losses of various materials by Efficiency-Limiting Bulk Recombination Analysis (ELBA) (Fig. 2).

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

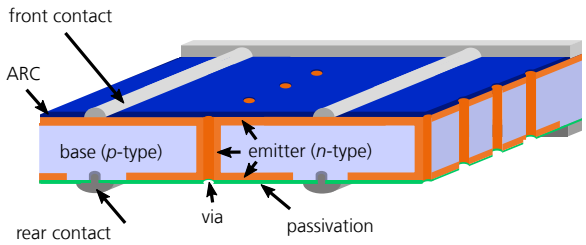
1

2

TECHNOLOGICAL DEVELOPMENT FOR SOLAR CELLS FROM UMG SILICON

The production of solar cells from less pure silicon feedstock allows significant savings in the costs for raw materials. In order to produce efficient solar cells from this material, we have successfully developed new technology to produce silicon blocks, wafers and solar cells. We have developed the BSK cell concept to make use of upgraded metallurgical grade silicon (UMG-Si) with purity down to 99.999% (5N) ("BSK" is from the German "beidseitig sammelnd und kontaktierbar", referring to a double-sided emitter and contacts on both surfaces). We demonstrated efficiency values exceeding 17% for cells made of multicrystalline wafers from commercially available UMG feedstock.

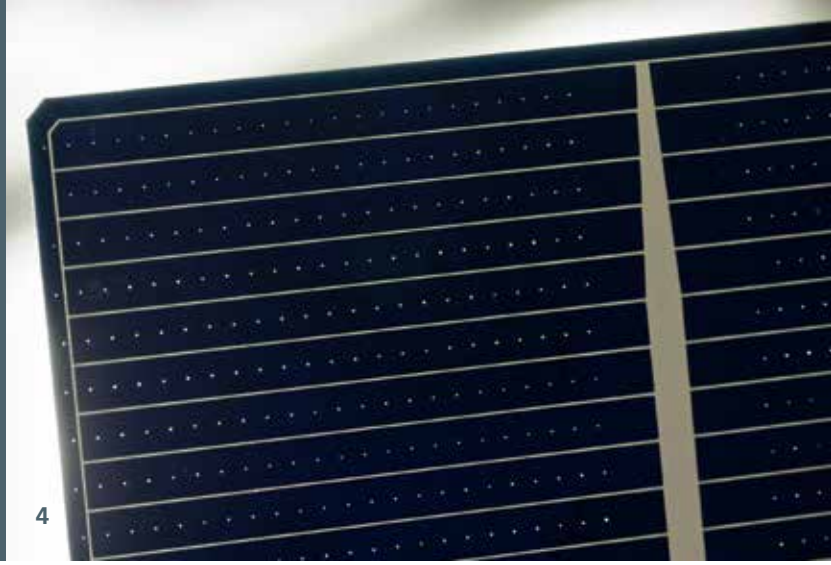
Daniel Biro, Florian Clement, **Fabian Fertig**, Fridolin Haas, Philipp Häuber, Karin Krauß, Stefan Reber, Stefan Rein, Stephan Riepe, Mark Schumann, Andreas Bett, Ralf Preu



5 *Structure of the BSK solar cell ("BSK" is from the German "beidseitig sammelnd und kontaktierbar", referring to a double-sided emitter and contacts on either side).*

The application of UMG-Si (Fig. 1) for the production of silicon blocks (Fig. 2) and wafers (Fig. 3) demands further development of established technology such as the vertical-gradient freeze process used at Fraunhofer ISE and multi-wire sawing. Due to the higher concentrations of dopants and impurities in the feedstock, both the crystallization process and also the crucible system used in the furnace must be optimised. We were able to induce the specific resistance which is favourable for solar cells by deliberate further doping during the solidification process and thus prevented the silicon from switching from p-type to n-type. Detection of silicon carbide and silicon nitride precipitates in the bricks cut from blocks by infrared methods is possible only to a limited extent due to the absorption properties of the compensated silicon. Thus, by optimising the gas flushing over the silicon melt and adapting the thermal solidification profile, we have produced blocks which do not contain any precipitates in the bulk which are detrimental to multi-wire sawing.

As silicon wafers of feedstock materials with a reduced impurity of 4N and 5N typically feature short charge carrier lifetimes and high base doping, we have developed the BSK solar cell which is specifically adapted to these properties. The structure (Fig. 5) is distinguished by emitter zones on the front and back surfaces which are connected by vias (Fig. 4). This means that charge carriers which are generated near the back surface are also collected efficiently. The contact grid on the back surface allows bifacial usage and thus a further increase in generated electricity. The yield of this type of PV system can be significantly increased by bifacial application. The stan-



dard bus bar configuration allows conventional connection technology to be used. With two additional steps compared to the standard solar cell process (Al back surface field BSF), the process complexity is low and corresponds to that for a passivated emitter and rear cell (PERC).

Within the project, the cell structure was simulated in detail, and an initial technological processing route was developed and tested on different materials. Compared to Al-BSF cells, an absolute efficiency gain of 0.4–0.6% on average and 0.5–0.6% for the maximum was achieved for heavily doped materials of differing purity. By contrast, no gain was observed for "electronic grade" (EG) silicon that had not been heavily doped, as expected (Fig. 6). Despite the very early stage of development for the BSK cell structure, the efficiency values for PERC solar cells have already almost been achieved and even exceeded for extremely inexpensive 4N silicon.

As part of a comprehensive economic evaluation, it was demonstrated that the BSK concept on UMG-Si has a significant cost advantage in levellised electricity generation costs compared to Al-BSF and PERC concepts if savings of 50% in the feedstock price are assumed. This emphasises the economic relevance of the new concept.

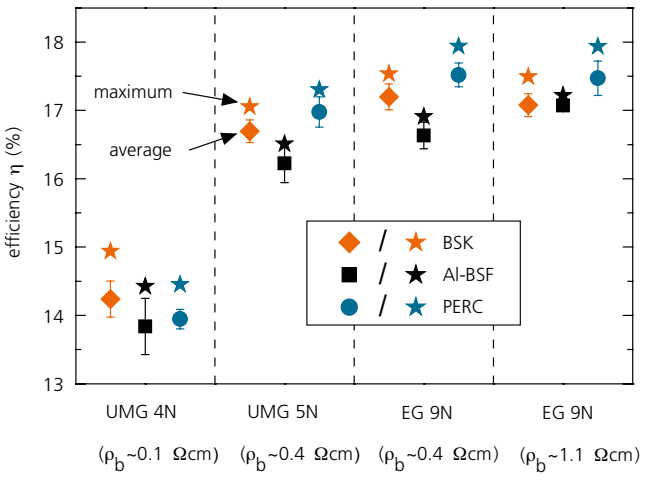
As a central result of the "Silicon Beacon" project, which was supported by the Fraunhofer-Stiftung, it was shown that the cost reduction in the silicon price combined with optimised crystallization and cell production technology can reduce the levellised cost of electricity generation.

1 *UMG-Si feedstock.*

2 *Silicon crystal from 12 kg UMG-Si feedstock with a purity of 5N (99.999% Si).*

3 *Multicrystalline silicon wafer from UMG-Si feedstock.*

4 *BSK solar cell: The vias, which serve to contact the back-surface emitter with the front surface, are visible as rows of light dots.*



6 *Average and maximum efficiency values for BSK, Al-BSF and PERC solar cells of multicrystalline material with different base resistivity values from UMG-Si feedstock of low purity down to 99.99% (4N) and 99.999% (5N) and high-purity EG-Si feedstock (9N). Each cell has an area of 156 mm x 156 mm. All measurements were made on a non-reflective chuck, i.e. bifacial gains have not been taken into account for the BSK solar cells.*

1

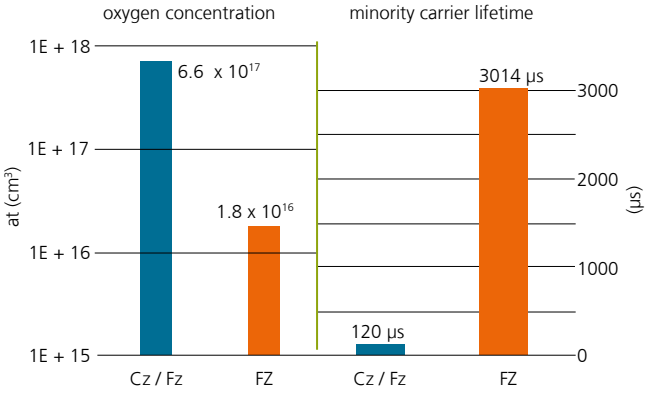
FLOAT-ZONE CRYSTALS FROM PRE-FORMED FEED RODS

Float-zone crystals feature a very low oxygen content and very high minority carrier lifetimes. Thus, float-zone wafers are predestined for use in high-efficiency cells or cells with minimal degradation effects. So far, the lack of suitable feedstock material has prevented float-zone silicon from penetrating the market, although the float-zone process as such has a better cost structure than the conventionally used Czochralski process. The float-zone process does not require crucibles and operates at higher crystallization rates.

Rainer Barth, **Peter Dold**, Thorsten Eckardt, Malte Ernst, André Henkel, Roland Kunert, Stefan Wieczorek, Frank Zobel, Andreas Bett

1 *Float-zone monocrystals, produced from pre-formed feed rods. Diameter: 4".*

Our approach is based on remelting standard solar silicon (chunks, granulate, broken wafers) into rods suitable for use as feed rods for the float zone process. We have developed a modified process for the pulling of feed rods, which ensures high productivity by rapid crystallization and pulling several rods from one crucible. As losses in structure do not play a role when feed rods are being pulled, we achieve a yield of 100%.

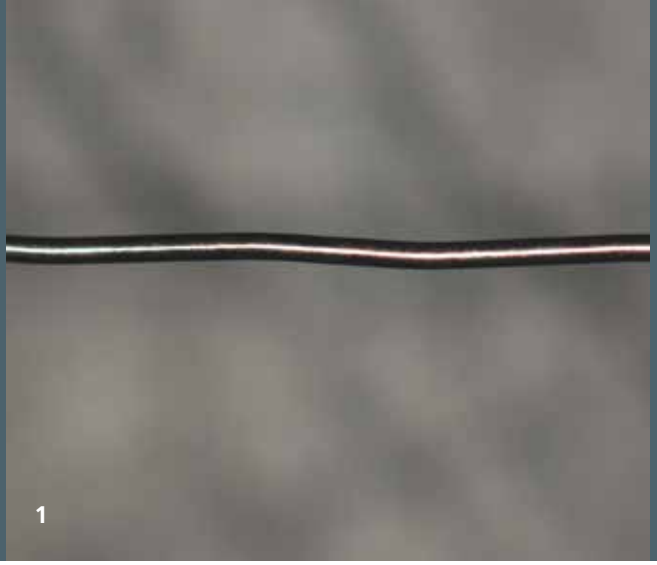


2 *Oxygen concentration and minority carrier lifetimes in pre-formed feed rods (blue) and the 4" FZ crystals (orange) produced from them. The oxygen concentration can be reduced by more than an order of magnitude, the carrier lifetime increases by a factor of 25. Oxygen detection: FT-IR (CiS, Erfurt); lifetime: QSSPC (quasi-steady-state photoconductance) (CSP-ZTN Halle).*

The pre-formed feed rods are then converted into 4" float-zone crystals in a float-zone reactor (FZ-14, PVA TePla). P-type and n-type crystals of differing resistivity were produced (Fig. 1) and characterized electrically and spectroscopically. With an oxygen concentration in the range of 1–2 x 10^{16} at/cm³ and minority carrier lifetimes exceeding 2 ms, these wafers are characterized by significantly better properties than normal monocrystalline ingots (Fig. 2).

Producing feed rods from commercially readily available solar silicon thus allows inexpensive production of wafers of high material quality. In the next step, we will increase the diameter of the float-zone crystals by steps from 4" to 8".

The "FZ-Sil" project was supported by the German Federal Ministry of Education and Research (BMBF) within the Solar-Valley Cluster of Excellence.



SLURRY-BASED WIRE-SAWING PROCESS WITH STRUCTURED WIRES

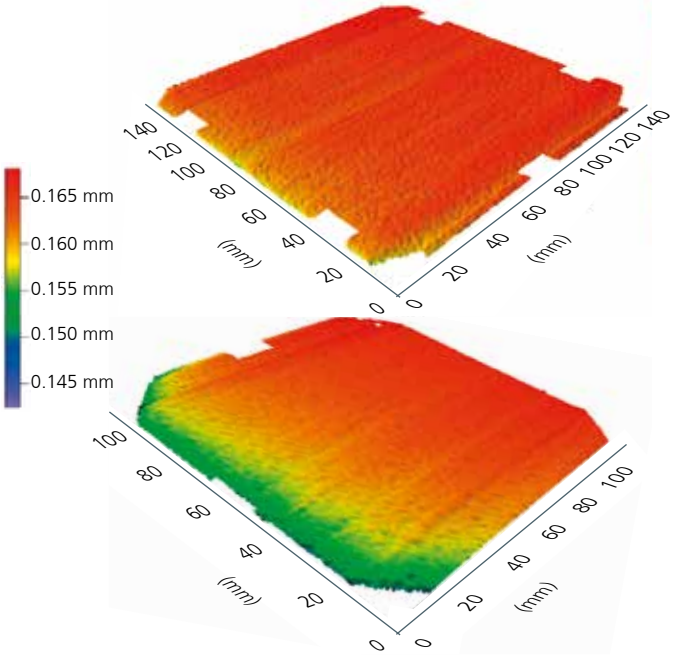
Most of the solar cells around the world are based on wafers which are produced from silicon crystals by wire-sawing. In the wire-sawing process, the crystal is pressed against several hundred wire loops and sawn into wafers with the help of an abrasive medium. Our further development of this sawing technique involves investigating the use of structured wire instead of the straight wire currently used. The structured wire enables higher feed rates and thus significant cost savings for the wire-sawing process. Our investigations concentrate on the effect of process parameters, which determine the wafer geometry and throughput decisively.

Philipp Häuber, Stephan Riepe, Devid Sabo, **Bernd Weber**, Andreas Bett

The standard, industrially applied sawing process, which is based on the use of a silicon carbide slurry and straight steel wire, has the disadvantage that the wafers are wedge-shaped after sawing. By using structured wire, we were able to produce wafers which have a more uniform thickness over the entire area and thus have a much less pronounced wedge form. Structuring the sawing wire (Fig. 1) ensures that the slurry enters the groove more efficiently, resulting in a more stable sawing process, so that no sawing marks or inhomogeneities are visible on the wafer surface (Fig. 2). In addition, the processing time is significantly shortened, as the sawing efficiency is increased by the wire structure, allowing higher feed rates. With the structured wire, we achieved a reduction of up to 50% in the thickness variation over the wafer area, accompanied by an approximately 30% higher feed rate compared to straight wire (Fig. 3). A further advantage is that the currently used slurry saws need to be only slightly modified to accept structured wire. These advantages apply to the sawing of both monocrystalline and multicrystalline silicon. Thus, the

1 *Microscope image of a structured wire.*

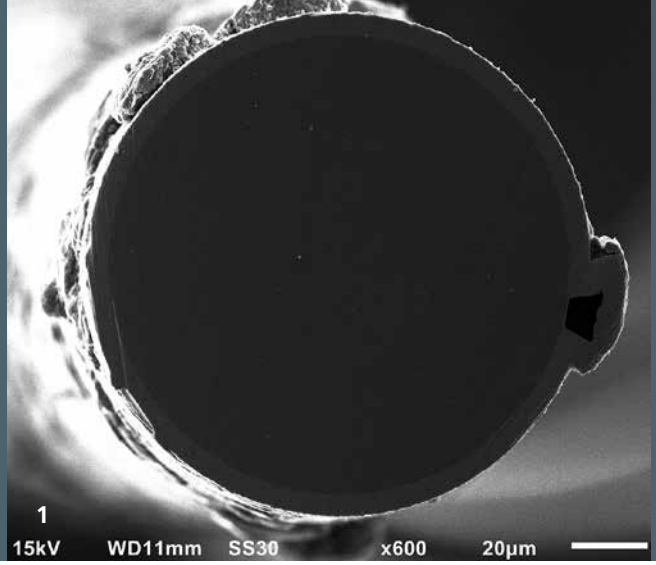
2 *Monocrystalline wafer with minimal thickness variation, which was sawn with structured wire.*

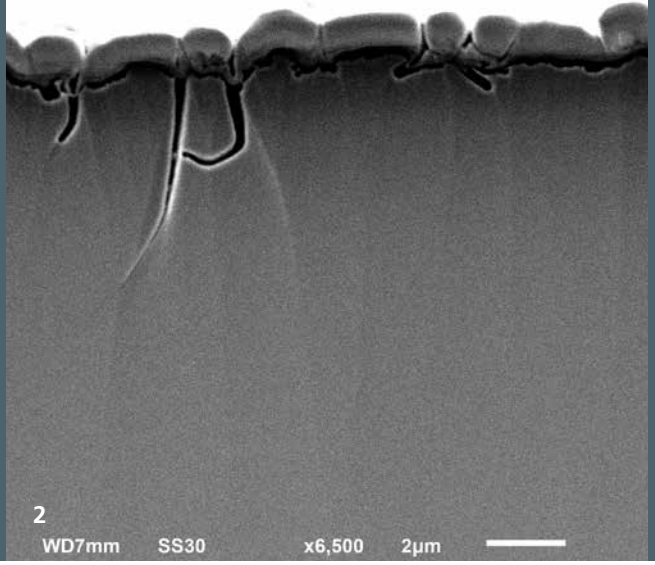


3 *Thickness distribution of a monocrystalline wafer with an area of 156 x 156 mm² and 125 x 125 mm², which was sawn with the structured wire (above) and straight wire (below). The scaling has been chosen such that the surface properties are clearly visible.*

structured sawing wire is ideally suited to achieve significant cost savings with existing equipment while simultaneously improving wafer quality.

The work was supported by the Fraunhofer-Stiftung and the European Commission within the "20plµs" project.



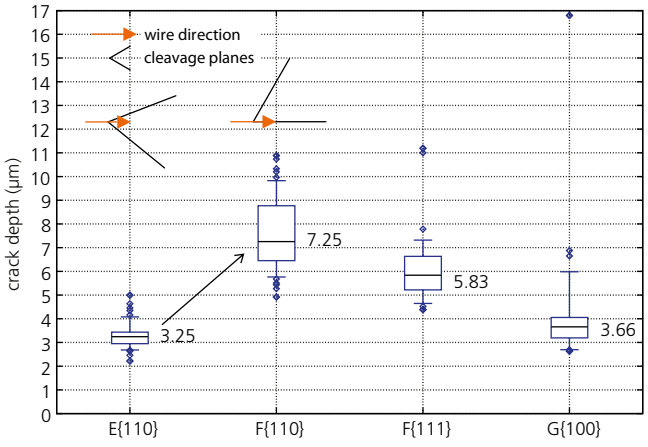


SILICON WAFER PRODUCTION WITH DIAMOND-COATED SAWING WIRE

Wafer production with diamond-coated sawing wire is a promising sawing technique offering an alternative to the conventional slicing process with loose abrasives. The main technological difference is the coating of the sawing wire with fixed, abrasive diamond particles. This results in a microscopically different ablation process. Research and further development of this slicing technology is a major field of work at the Fraunhofer Technological Centre for Semiconductor Materials THM. Our results show that surface damage of monocrystalline and multicrystalline silicon material depends on crystal orientation.

Rajko Buchwald, Marcel Fuchs, Killian Fröhlich, Hans Joachim Möller, Stefan Retsch, Sindy Würzner, Andreas Bett

The application of diamond-coated wires to sawing silicon wafers is relatively new, such that there is a great need for process development. For industrial application of this technology, investigations, including some fundamental research, and innovative process optimisation are needed. The technical and analytical equipment of Fraunhofer THM is oriented toward this research goal. For the sawing experiments, we use a technically optimised, industrial multi-wire saw and have equipped it with additional measurement technology. It was used to produce wafers of monocrystalline and multicrystalline silicon and characterize their surface, micro-crack and fracture properties with specially adapted or optimised optical and mechanical measurement systems. Analysis of these parameters allows not only the sawing process to be improved, but also the resistance to fracture of wafers to be determined and optimised on an industrial scale. Our investigations have demonstrated that the maximal crack depth on a wafer varies as a function of the crystal orientation by a factor of 2 (Fig. 3). For surfaces with a {110} orientation, two cleavage planes are present perpendicular to the surface. Depending on the angle between the sawing wire and the cleavage planes, the crack depth can increase by 123% in the most unfavourable case. This can result in a reduced fracture stress, which was confirmed by fracture tests.

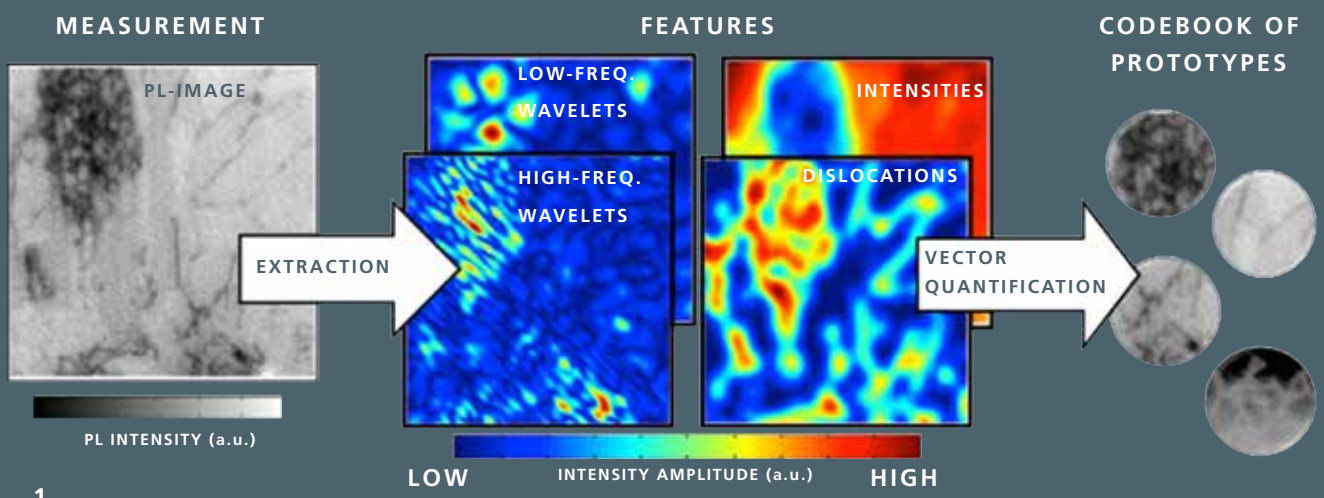


3 *Maximum crack depth as a function of surface crystal orientation for a multicrystalline silicon wafer.*

1 *High-resolution scanning electron micrograph of the crosssection through a diamond-coated sawing wire. The nickel coating around the wire core and one exposed diamond are visible.*

2 *Scanning electron micrograph of a wafer cross-section to determine the depth of micro-cracks. The cross-section is oriented perpendicular to the sawing direction. The micro-cracks are visible as dark contrast zones surrounded by light edges.*

The work was supported by the European Regional Development Fund (ERDF), the German Federal Ministries for the Environment, Nature Conservation and Reactor Safety (BMU) and of Education and Research (BMBF), the Saxon State Ministry for Sciences and Arts (SMWK) and the Sächsische AufbauBank (SAB).



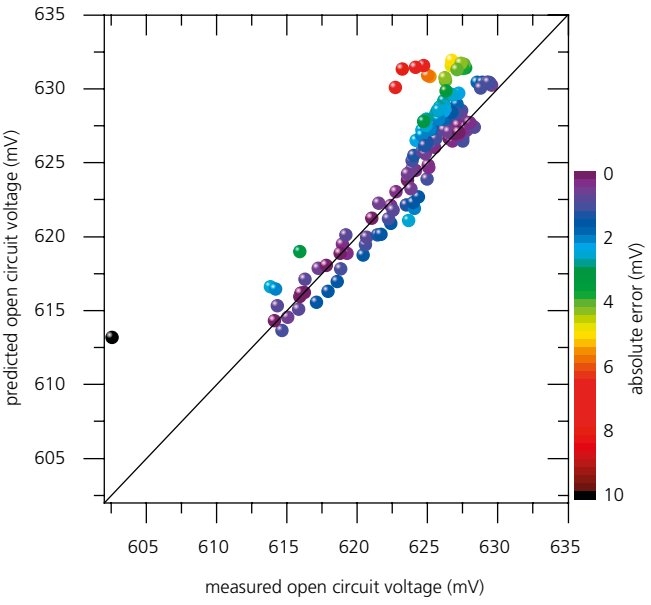
PREDICTION OF SOLAR CELL PARAMETERS FROM MULTICRYSTALLINE WAFERS

Quality control of multicrystalline silicon wafers presents a major challenge to the PV industry. It is essential for solar cell manufacturers to identify and remove low-quality material during the input control. Photoluminescence (PL) images of the raw wafer allow relevant crystallization defects to be detected. In order to quantify the defects, powerful image-processing algorithms must be developed. Classification schemes to evaluate the material are derived from the defect characteristics. These must also be able to reliably evaluate the material from an unknown block or manufacturer. The goal is to develop a robust quality-control procedure and to establish it as a global standard.

Matthias Demant, Jonas Haunschild, Stefan Rein, Ralf Preu

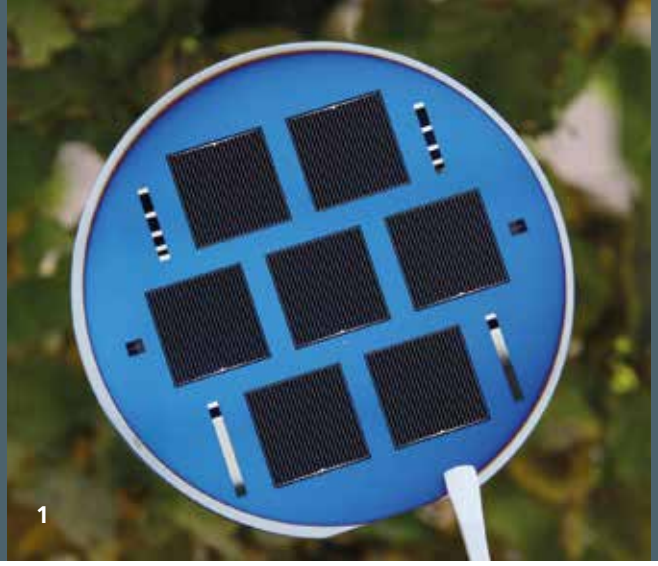
The measurement of photoluminescence has developed into a key technology to assess the material quality of mc-Si wafers. Numerous crystallization defects are visible in the spatially resolved images. Defect characteristics are superimposed in the images and vary strongly in their distinguishing features. This presents a special challenge to interpreting the data. To differentiate and quantify the defect characteristics, pattern recognition methods were developed to describe the wafer on the basis of representative defect structures (Fig. 1). Further relevant measured values such as the doping concentration and carrier lifetimes were added. The suitability of this description to assess material quality was tested in an extensive experiment with silicon blocks from different manufacturers. The large data set was used together with machine-learning methods to train a model to predict the open circuit voltage of the subsequent solar cell. When the procedure was applied to a completely "unknown" block, the open circuit voltage was predicted with an average absolute error of 1.7 mV (0.3%$_{rel}$) (Fig. 2).

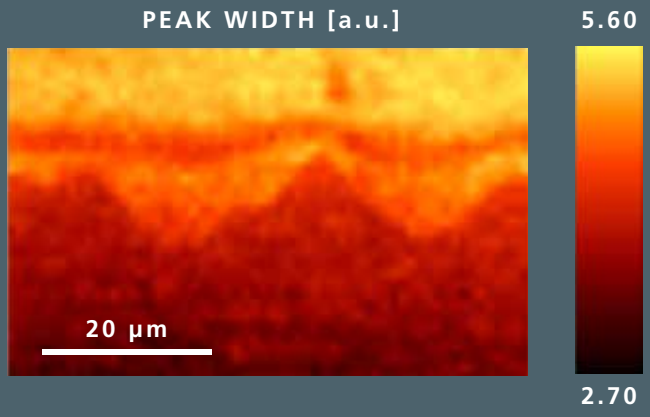
1 *Various characteristics are extracted from the PL image. Among other approaches, wavelets are used to represent each image sector as the superposition of spatially localised waves of differing extent and frequency. Frequently occurring combinations of characteristics are recorded as typical PL structures in a codebook. The wafers are described and evaluated on the basis of the distribution of the PL structures which occur.*



2 *Applying the procedure of Fig. 1, prototypical characteristics were extracted from PL images of untreated wafers and used to train a model to predict the open circuit voltage. The graph shows the prediction result for the open circuit voltage of 164 wafers from three bricks of an unknown block. The small relative deviation of less than 0.3% on average demonstrates the suitability of the procedure.*

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





1 2

SOLAR CELLS WITH EPITAXIAL EMITTERS AND 20% EFFICIENCY

The preparation of emitter layers is an important processing step in the production of solar cells. Emitters are normally produced by diffusion of boron or phosphorus. The limits of diffusion become evident in the industrial implementation of advanced cell concepts with efficiency values exceeding 20%, for which deeply buried emitters are advantageous. An alternative technology requiring only one tenth of the processing time is epitaxial growth of silicon layers. These epitaxial layers allow appropriate and optimised emitters to be manufactured with independently adjusted depth and dopant concentration.

Jan Benick, Elke Gust, Martin Hermle, Stefan Janz, Martin Keller, Harald Lautenschlager, Nena Milenkovic, **Thomas Rachow**, Stefan Reber, Bernd Steinhauser, Andreas Bett, Stefan Glunz

Demonstrating efficiency values that exceeded 20% with solar cells incorporating epitaxial emitters was the goal of the "EpiEm" project, which we carried out in co-operation with RENA. To achieve this, not only was it necessary to grow low-defect epitaxial layers on monocrystalline and multicrystalline silicon, but also the high-efficiency solar cell processes had to be adapted to the new emitter. After intensive characterization of the boundary layers and the crystal structure (Fig. 2), and parallel process optimisation, we succeeded in improving the emitter quality significantly. As a result, epitaxial emitters suitable for high-efficiency cells, with saturation currents below 50 fA/cm^2, are now available.

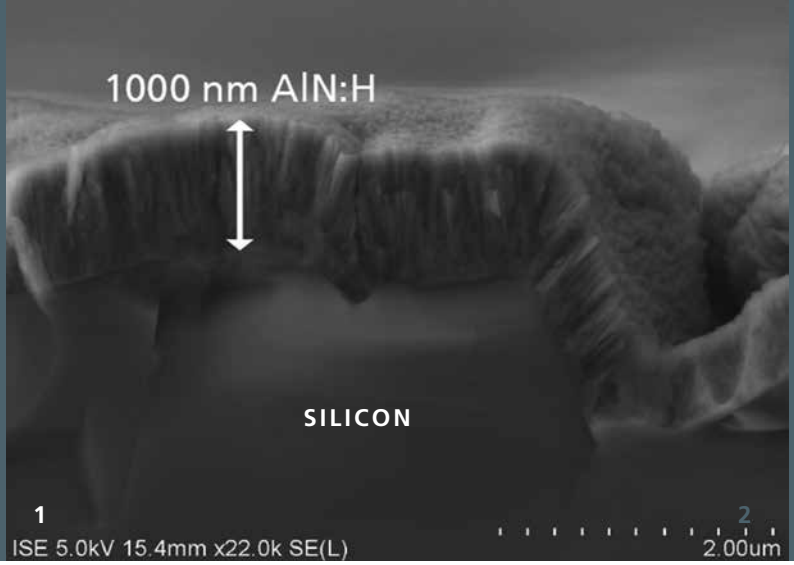
1 *20 x 20 mm² n-type PERL solar cells with epitaxially grown emitters. The cell concept includes an aluminium oxide passivation layer with a SiN_x anti-reflective coating and a passivated back surface based on a-SiC, with local contacts.*

2 *Example of a micro-Raman measurement of an epitaxial emitter grown on a surface with pyramidal texture. This powerful measurement method provides important information e.g. on stress, doping concentration or recombination.*

An essential advantage in comparison to diffusion is that different types of doping can be produced without fundamentally changing the deposition process. Integration into the solar cell process was thus carried out both on n-type and p-type wafers with adapted PERL cell concepts (Fig. 1). The resulting solar cells had an efficiency value of 20% and a fill factor exceeding 81%, which documents the potential of the epitaxial emitter.

The advantages of the epitaxial emitter – such as avoidance of several, previously necessary masking and etching steps, and greater tolerance to firing – should be achieved in future in industrial solar cell processes and the cost reduction potential demonstrated experimentally. An important goal of the work is to transfer the epitaxial process to our high-throughput deposition reactors.

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



SPUTTERED ALUMINIUM NITRIDE FOR PASSIVATION OF SOLAR CELLS

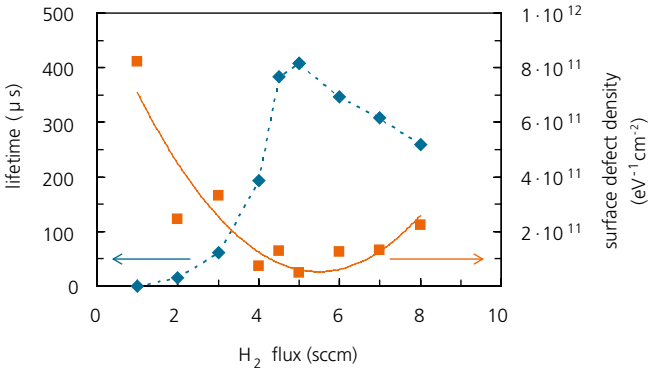
A key to achieving the highest possible efficiency is optimal passivation of the silicon surfaces. This is the only way to prevent the electron-hole pairs that were generated by the incident light from recombining before they can contribute to externally useful electricity. However, the established procedures for surface passivation all have significant disadvantages. For example, some require expensive materials or have low coating rates (e.g. ALD). We have developed a coating consisting of sputtered, hydrogenised aluminium nitride (AlN:H) that is completely new for solar cells. This coating should combine a very good passivation effect, thermal stability and a cost-effective deposition method.

Georg Krugel, Jochen Rentsch, **Winfried Wolke**, Ralf Preu

Aluminium nitride has been used for some time in optoelectronics or sensorics because of its good optical and electronic properties. However, the material has not been used to date in the photovoltaic sector and is almost unknown.

The sputtering technique was used to develop the new coating. This technology has proven to be cost-effective and easily upscaled in PV applications, as well as offering a wide variety of deposition conditions. The approach was chosen of sputtering from two aluminium targets with medium frequency in argon and nitrogen atmospheres. Accurately defined quantities of hydrogen were also added. After optimisation of the hydrogen flux, the coatings prepared in this way showed excellent passivation properties due to a very low defect density (Fig. 2). These values were also achieved after a high-temperature processing step. In addition, the coatings have very good anti-reflective properties, with a refractive index of

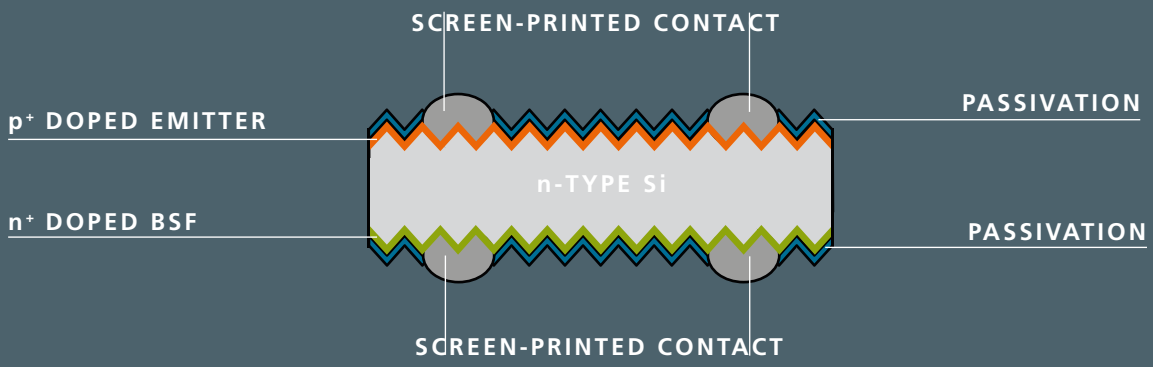
1 *Scanning electron micrograph of sputtered aluminium nitride on a silicon wafer.*



2 *Charge carrier lifetime and defect density of sputtered aluminium nitride versus hydrogen flux determined during deposition. Coating of p-type, 1 Ωcm FZ wafers. After further process optimisation, values exceeding 1000 µs were achieved (not shown here).*

n = 2, low absorptance and very good passivation of standard emitters (J_{0e} around 100 fA/cm²). Not only phosphorus-diffused but also boron-diffused emitters were investigated, which were also passivated very effectively by AlN:H.

Our conclusion is that applying AlN:H on the front surface of the solar cell instead of the conventionally used SiN:H, and also using it for back-surface passivation, is an extremely promising approach to increase solar cell efficiency.



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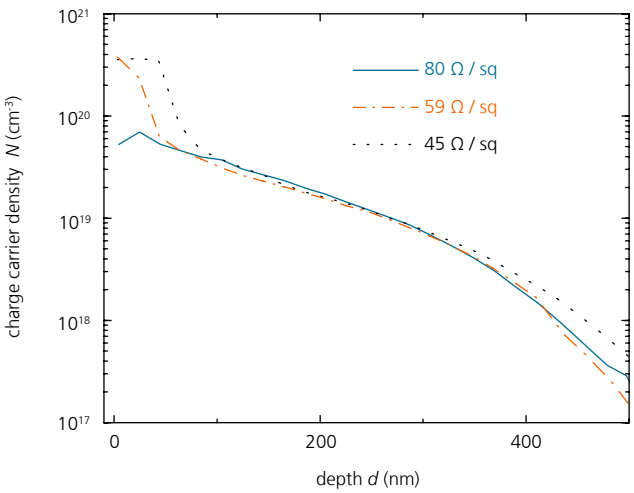
INDUSTRIALLY APPLICABLE CO-DIFFUSION PROCESSES FOR N-TYPE Si SOLAR CELLS

Usage of n-doped silicon (Fig. 1) is one option to increase the efficiency of Si solar cells. The current challenge is to identify industrially applicable processes. Here, the diffusion process assumes a key role. N-type solar cells usually contain two or more regions created by diffusion. One approach to reduce costs is co-diffusion, in which the required doped regions are created in a single high-temperature step. At Fraunhofer ISE, a co-diffusion process was developed which is based on using conventional phosphorus tube furnace technology, and thus helps appreciably to reduce the effort needed to convert existing production lines to n-type Si technology.

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

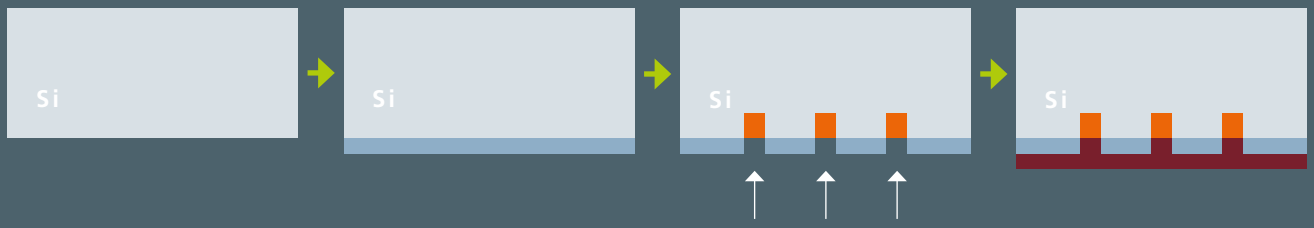


2 *Different phosphorus doping profiles created in co-diffusion processes and the associated sheet resistance. The phosphorus doping profile of the BSF can be deliberately adjusted without changing the boron doping profile of the emitter.*

1 *Schematic representation of a bifacial, industrially produced n-type solar cell.*

The approach adopted by Fraunhofer ISE consists of developing an industrially applicable production process based on equipment which is already used in solar cell production and which requires as few additional process steps as possible. A boron-doped oxide layer is deposited onto one wafer surface by atmospheric pressure chemical vapour deposition and then phosphorus diffusion is carried out in a conventional quartz tube furnace. In this process, the previously deposited, boron-doped layer serves as the source to create the p⁺ doped emitter, while phosphorus diffuses from the gas phase into the uncoated side of the wafer to create the n⁺ doped back surface field (BSF) (Fig. 1). This process sequence means that several process steps can be avoided in comparison to sequential diffusion. Controlled diffusion of the phosphorus presents a major challenge, as high temperatures are needed for the simultaneous boron diffusion. The process developed at Fraunhofer ISE makes it feasible to adjust both the surface doping concentration needed for contacting and the depth of the phosphorus doping profile independently of the boron doping (Fig. 2). The first solar cells produced by co-diffusion achieved an efficiency value of 18.4% (n-type Cz-Si wafer, 156 mm edge length).

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



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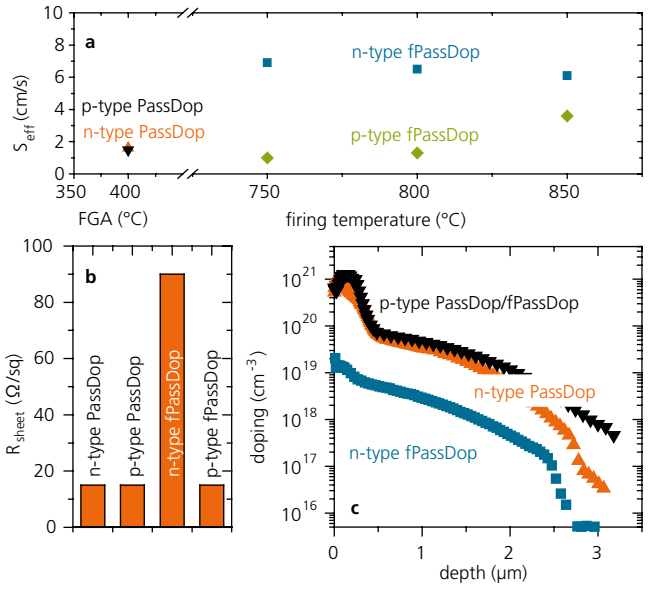
PASSDOP PROCESS: INDUSTRIALLY RELEVANT PRODUCTION OF A PERC STRUCTURE

Efficient and cost-effective processes are required for industrial production of back-surface passivated and locally contacted solar cells. The PassDop process can be used for cells on either n-type or p-type silicon. A dielectric coating is deposited onto the back of the cell which not only passivates the surface but also contains a dopant which is subsequently driven into the silicon by a laser process. In this process, the coating is locally ablated, so that then the metal for the back contact can be applied directly by evaporation. With this process, we have succeeded in producing n-type solar cells with efficiency values up to 23.5%.

Jan Benick, Martin Hermle, Ulrich Jäger, Antonio Leimenstoll, Muhammad bin Mansoor, Felix Schätzle, Sonja Seitz, Bernd Steinhauser, Nadine Weber, Stefan Glunz

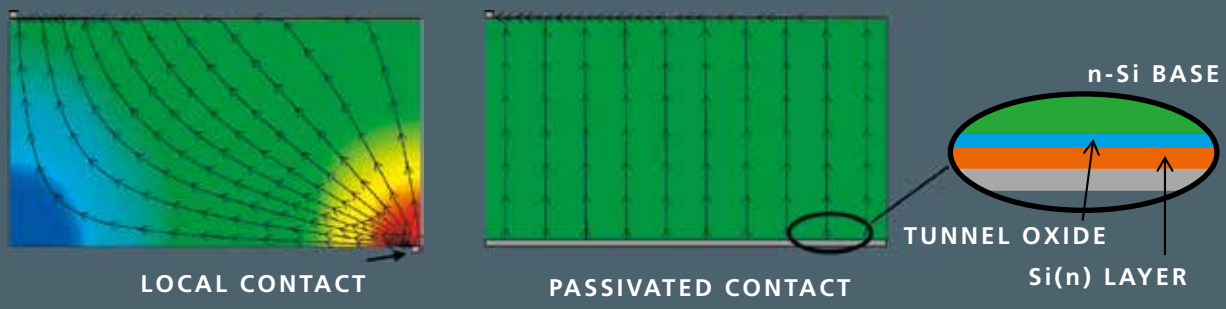
Many cell concepts for highly efficient silicon solar cells feature a passivated back surface with heavily doped zones under local contacts. To produce such a structure industrially, processes are required which allow the structure to be generated effectively and which are able to guarantee the industrially demanded throughput at low cost. By combining CVD and laser processes, the PassDop process is fundamentally able to meet these criteria. Due to the double functions of the individual process components (surface passivation / dopant source, contact opening / local doping), the relatively complex structure is implemented by a very lean processing sequence, without negative effects on the quality. The process can be used for either n-type or p-type solar cells by appropriate choice of the dielectric layer and the dopant. The measured electric properties (passivation, doping) from the PassDop process on n-type and p-type surfaces are illustrated by examples in Fig. 2. With a surface recombination rate of less than 10 cm/s, excellent passivation can be achieved also after the firing step for p-doped and n-doped coatings.

1 *Processing sequence for the PassDop process.*



2 *Properties achieved with the PassDop process on n-type and p-type surfaces: a) Passivation quality as a function of subsequent firing temperature; b) Sheet resistance of the local doping; c) doping profiles of the local doping.*

The local laser doping from the PassDop layers is also very effective; sheet resistances of 30–80 Ω/sq can be achieved, but there is still potential for improvement specifically in the n-fPassDop process. Solar cells with an efficiency value of 23.5% were successfully produced with the PassDop process on n-type silicon.



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PASSIVATED CONTACTS FOR HIGH-EFFICIENCY SILICON SOLAR CELLS

Due to ongoing improvements in material quality and surface passivation, recombination at the metal contacts has become one of the dominant loss mechanisms in silicon solar cells. This loss can be reduced by using so-called passivated contacts, which suppress the recombination of minority charge carriers and simultaneously allow lossless majority charge carrier transport. On the basis of an extremely thin dielectric tunnel oxide, we have succeeded in producing a very effective, passivated contact (TOPCon), which simultaneously passivates the surface excellently and constitutes low resistance to charge carrier transport.

Jan Benick, Martin Bivour, **Frank Feldmann**, Martin Hermle, Antonio Leimenstoll, Christian Reichel, Felix Schätzle, Christian Schetter, Sonja Seitz, Maik Simon, Harald Steidl, Nadine Weber, Karin Zimmermann, Stefan Glunz

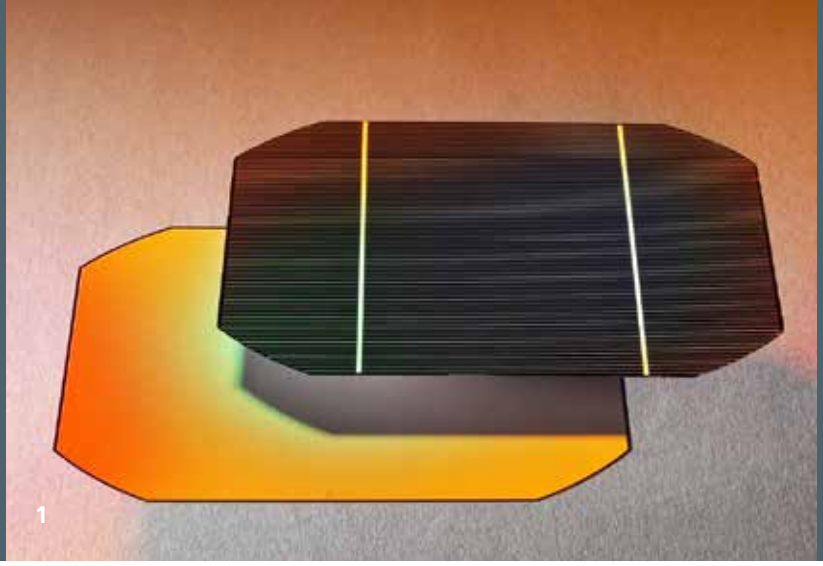
To increase the efficiency of silicon solar cells, the PERC concept (Passivated Emitter and Rear Cell) is being transferred to industrial production. Higher voltages can be achieved due to the dielectric surface passivation and the reduction of the metallized area down to contact points. However, the gain in voltage is accompanied by higher series resistance, as the charge carriers must travel longer distances within the silicon. Optimising this type of structure demands a trade-off between high voltage (long distance between contact points) and high fill factor (short distance between contact points).

One possibility to avoid this trade-off is to use carrier-selective contacts which cover the whole surface, also called "passivated contacts". The challenge associated with these contacts is that they must both suppress the recombination of minority charge carriers and simultaneously allow lossless majority charge carrier transport. At Fraunhofer ISE, this type of contact was developed on the basis of an extremely thin tunnel oxide and a thin silicon layer (Tunnel Oxide Passivated Contact, TOPCon), and implemented in high-efficiency solar cell structures.

1 *Simulated current transport in a locally contacted solar cell (left) and in a solar cell with the newly developed passivated TOPCon base contact (right).*

The long effective lifetimes measured for the TOPCon structure confirm the very good passivation properties of the layer stack used. As the silicon oxide which is used as the tunnel oxide also forms a barrier to the majority charge carriers in principle, it must be kept so thin that the charge carriers can overcome it by quantum mechanical tunnelling processes. In order to investigate this charge carrier transport, highly efficient n-type silicon solar cells were produced with a diffused front-surface boron emitter and the TOPCon contact covering the entire back surface. Very high fill factors of more than 82% and voltages exceeding 700 mV confirm that the charge carrier transport through the tunnel oxide is almost completely free of losses. This demonstrates that a selective and excellently passivated contact was implemented with the TOPCon structure. Altogether, the TOPCon structure has been determined to be a simple und non-structured back contact, with which we were able to achieve efficiency values of up to 24% for high-efficiency n-type silicon solar cells.

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



SIMPLE N-TYPE SILICON SOLAR CELL CONCEPTS WITH PERC TECHNOLOGY

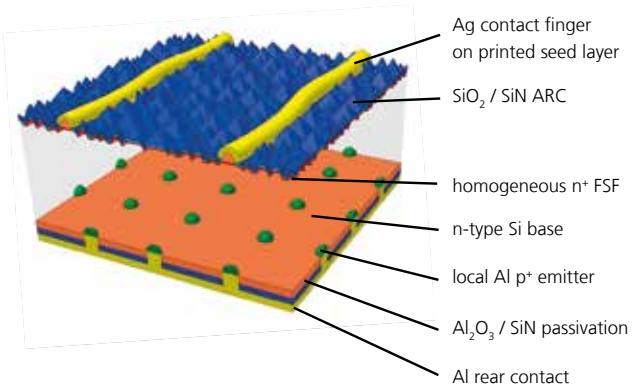
At present, p-type silicon is the main type of raw material for industrially produced solar cells. Although n-type silicon has better electrical properties, the most widely established, standard technology for cell production is for p-type Si. The combination of already widespread production processes with n-type material enables new, promising approaches for simply manufactured, highly efficient solar cells. In contrast to the complex cell structures on n-type Si which can already be found on the market, the concepts developed by Fraunhofer ISE now open the door to cost-effective production of n-type Si solar cells.

Markus Glatthaar, Michael Rauer, **Christian Schmiga**, Annika Tuschinsky, Stefan Glunz

Most of the solar cells sold around the world are manufactured of crystalline p-type silicon (Si). However, the material itself is already a limiting factor today for good, industrially produced cells. At present, the highest efficiency values are achieved with cell structures on intrinsically higher-quality n-type Si, but after applying special or complex processes.

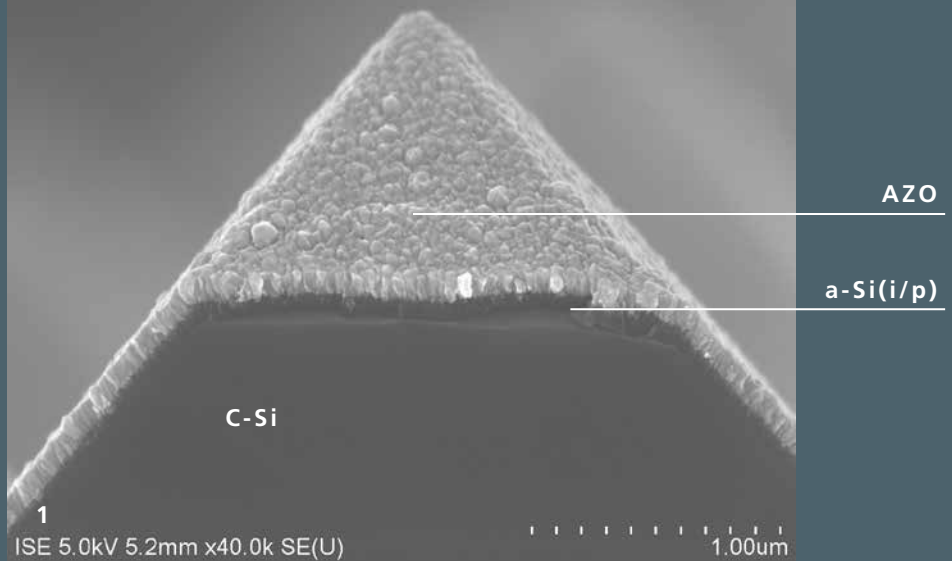
The easily implementable cell concepts developed at Fraunhofer ISE combine the well-proven production technology for p-type Si solar cells with n-type Si material. Aluminium-doped (Al) p^+ layers as the emitter on the back surface of the cell are decisive in this concept. They are prepared from screen-printed, metallic pastes containing Al in a short, high-temperature firing step by alloying into the Si surface, and form the Al back surface field (BSF) in conventional p-type cells. The application of Al-alloyed emitters thus enables the production of highly efficient n-type cells on the basis of established production processes.

1 *Large-area, n-type Si solar cell produced at Fraunhofer ISE with Al emitter points on the back surface and printed contacts on both surfaces.*



2 *Schematic representation of our n-type Si solar cell with back-surface Al emitter points. The well-known PERC technology for p-type cells can be applied for n-type cell production without essential changes.*

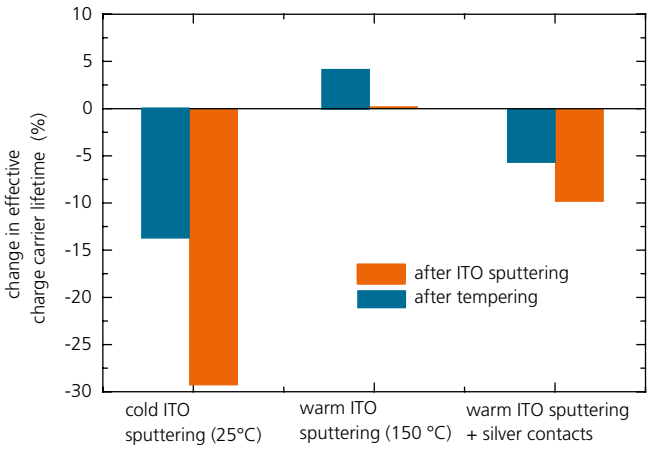
If the well-known PERC (Passivated Emitter and Rear Cell) technology from p-type Si solar cells is transferred to n-type Si material, a cell structure results which features many small local Al emitter regions, which are alloyed into the passivated Si back surface of the cell (Fig. 2). The structural and electrical properties of these point-formed or linear emitters were significantly improved by Al pastes that had been further developed at Fraunhofer ISE. As a result, our first large-area (144 cm^2), n-type cells prepared in this way (Fig. 1) already achieve a peak efficiency value of 19.7%.



PRODUCTION TECHNOLOGY FOR SILICON HETEROJUNCTION SOLAR CELLS

Silicon heterojunction solar cells are wafer-based solar cells with potential efficiency values exceeding 24%. In this type of solar cell, thin films of amorphous silicon (a-Si) are used for surface passivation and to create selective contacts on the front and back surfaces. The functionality of these films is very strongly affected during the production process by the quality of the preceding and subsequent processes. It is thus important to evaluate and optimise their effect on cell efficiency.

Martin Bivour, **Dietmar Borchert**, Lena Breitenstein, **Martin Hermle**, Stefan Hohage, Sven Holinski, Jan Jeurink, Laurent Kroely, Britt-Marie Meiners, Anamaria Moldovan, Jochen Rentsch, Kurt Ulrich Ritzau, Petra Schäfer, Winfried Wolke, **Martin Zimmer**, Karin Zimmermann, Stefan Glunz, Ralf Preu



2 *Relative change in the effective charge carrier lifetime, measured for silicon wafers that were bifacially passivated with Si layers, directly after the ITO sputtering processes and after tempering in air at 150 °C for 12 minutes.*

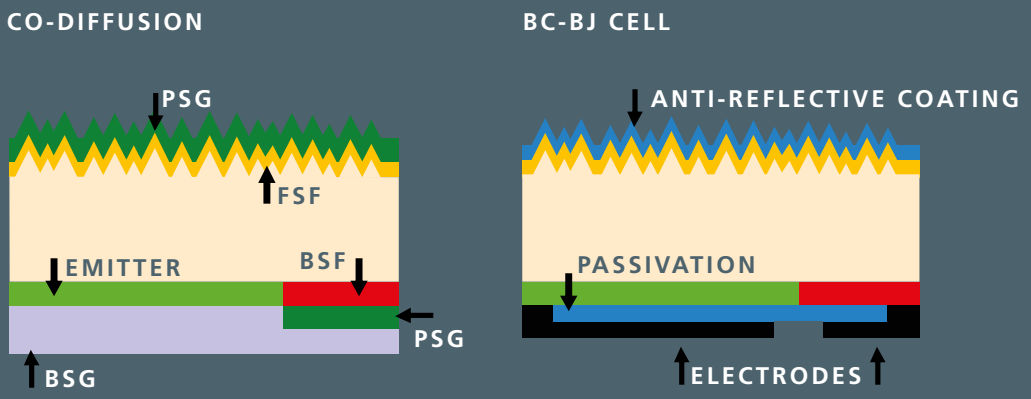
1 *Electron micrograph of the front surface of a silicon heterojunction solar cell. The pyramids on the surface, the thin a-Si layer and the contact layer can be seen. Aluminium-doped zinc oxide (AZO) was used instead of ITO.*

The electrical quality of the interface between the amorphous and the crystalline silicon depends strongly on the cleaning of the base substrate. We are developing new processing routes for this based on ozone, hydrochloric acid and hydrofluoric acid. These significantly simpler and less expensive cleaning processes have proven to be superior production technology compared to classic semiconductor cleaning sequences such as RCA cleaning.

The contacts for heterojunction solar cells consist of a sputtered indium tin oxide layer (ITO) over the whole surface plus an evaporated or printed grid of metal contacts. The ITO sputtering process strongly influences the passivation properties of the underlying a-Si layers. A cold ITO process reduces the passivation quality, which cannot be reversed by tempering. A warm process does not have any effect on the passivation quality. The evaporation of silver contacts leads to a reduction of 5% after tempering (Fig. 2).

To allow the most important cell properties to be predicted before metallization, a combination of quasi-static lifetime measurement (QSSPC) and the measurement of the external voltage under high irradiance levels (SunsVoc) was established to evaluate a-Si/TCO layers. This measurement methodology allows the effects of the doping efficiency, the passivation of the a-Si layers and the work function of the TCO on the resulting cell efficiency to be analysed.

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



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PROCESSES FOR INDUSTRIAL BACK-CONTACT SOLAR CELLS

Back-contact solar cells have an advantage over other cell types due to their potential efficiency, if cost-effective processes to manufacture them can be found. One approach involves co-diffusion processes, in which all of the required doped regions are created in a single high-temperature step. In addition, structuring methods which can be applied on an industrial scale are needed. Contact-free, highly accurate inkjet technology is a promising candidate. At Fraunhofer ISE, co-diffusion and inkjet structuring were applied to produce small-area, back-contact solar cells with efficiency values of up to 20.5%.

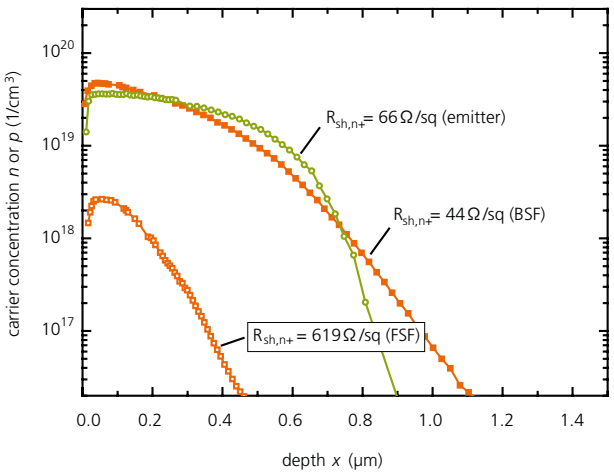
Daniel Biro, Raphael Efinger, David Hahn, Mike Jahn, **Roman Keding**, Achim Kimmerle, David Stüwe, Benjamin Thaidigsmann, Andreas Wolf, Ralf Preu

The differently doped regions of a back-contact back-junction (BC-BJ) solar cell are generally produced by a sequence of gas-phase diffusion processes. The resulting process chains are complex and cause high process costs. The approach developed at Fraunhofer ISE allows all doping processes to be integrated into a single high-temperature step by co-diffusion from pre-structured solid diffusion sources (Fig. 1). Silicate glasses doped with boron or phosphorus (BSG or PSG), which are applied by plasma-enhanced chemical vapour deposition (PECVD), serve as solid diffusion sources and allow the dopant concentration in the silicon to be controlled accurately (Fig. 2).

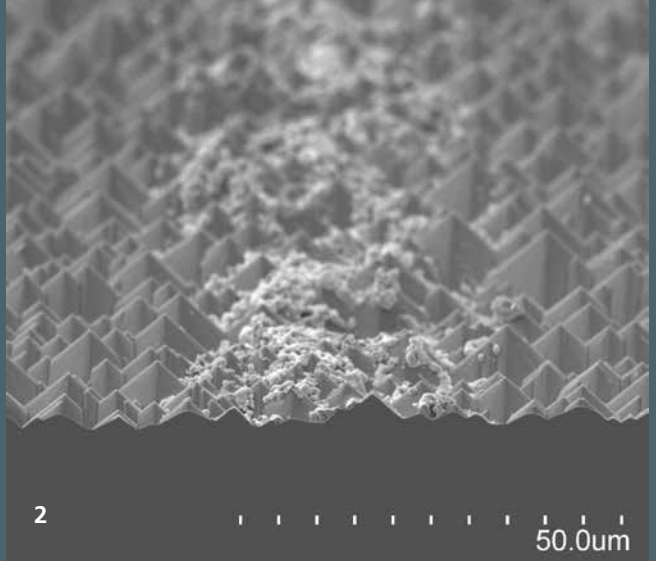
In addition, BC-BJ solar cells require finely resolved structures, which are implemented at Fraunhofer ISE with accurate and industrially scalable inkjet technology. The combination of printing etch-resistant inks with wet chemical etching processes allows structures to be produced with a structure width of less than 50 µm. In addition, the contact-free process allows very thin wafers to be used, so that material costs can be saved.

The first generation of BC-BJ solar cells were produced by co-diffusion and inkjet structuring and had an efficiency value of 20.5% (aperture area of 4 cm²). Future work has the goal of transferring the processes to large-area solar cells and further simplifying the process sequence.

1 *Schematic diagram of the BC-BJ cell during the co-diffusion step (left) and after completion of production (right).*



2 *Concentration profiles and sheet resistance of the dopants of a BC-BJ solar cell consisting of n+ back surface field (BSF), n⁺ front surface field (FSF) and p⁺ emitter. All doped regions were created in a single co-diffusion step. The doping profiles shown here were determined after a further high-temperature step (drive-in).*



HIGH-THROUGHPUT METALLIZATION WITH ROTARY PRINTING PROCESSES

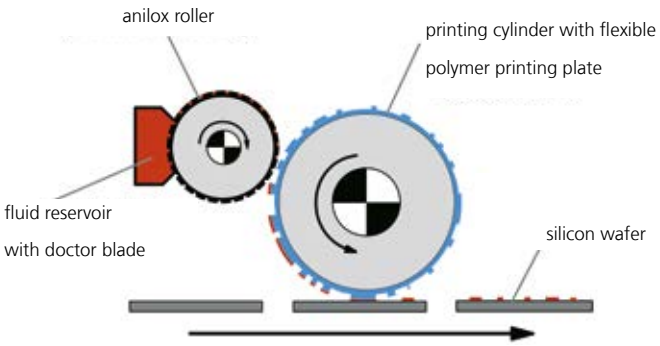
Metal contacts are applied to solar cells to conduct the generated electricity. The demands on the printing processes used are high: Extremely fine silver contact fingers on the front surface should shade as little active cell area as possible, but simultaneously ensure high conductivity. Cost-effective use of silver plays a major role in optimisation. Industrially manufactured solar cells are usually metallized by screen-printing processes – a well-established printing process, but with a limited throughput. Rotary printing processes have the potential both to increase throughput significantly and also to reduce silver consumption.

Jonas Bartsch, Daniel Biro, Florian Clement, Denis Erath, Andre Kalio, Michael Linse, **Andreas Lorenz**, Ralf Preu

1 *Solar cell (format: 156 x 156 mm²) with seed layer metallization produced by flexography.*

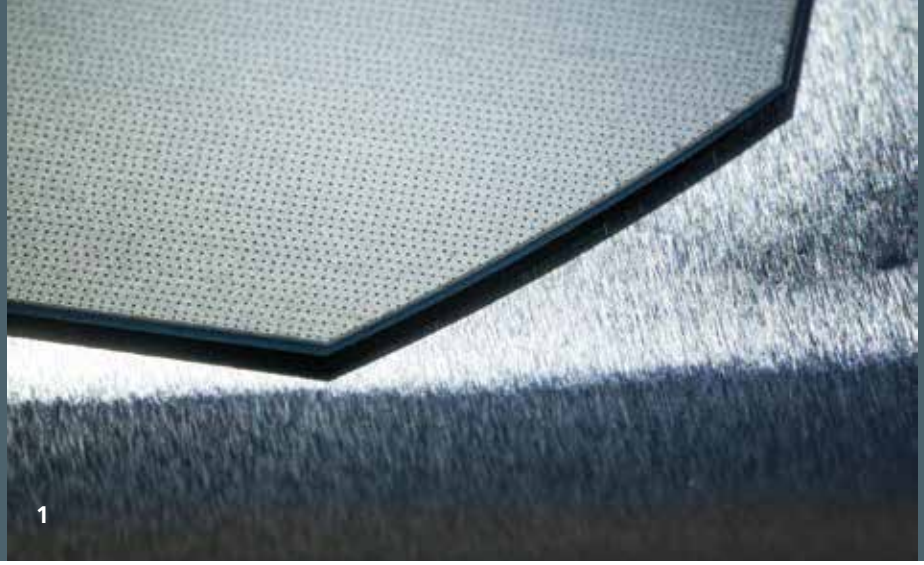
2 *Cross-section and scanning electron micrograph of a silver seed layer applied by flexography (width ~25µm).*

As an alternative to screen printing, the application of rotary printing processes is a very promising approach. These processes are used in numerous industrial sectors for extremely accurate transfer of printing inks and fluids onto all types of substrates. Rotary printing processes are distinguished by high throughput and thus high productivity, as well as greatest accuracy and reproducibility of the printed product. Modern roll-to-roll rotary printing presses achieve printing rates of 600 m/min and more. Throughputs on the order of 5,000 to 10,000 wafers/h are conceivable for solar cell metallization. For example, rotary printing processes can transfer seed layers very precisely for subsequent electro-plating based on copper. Compared to screen-printing processes, the silver consumption and thus the processing costs can be reduced.



3 *Schematic diagram of the flexography process: An engraved anilox roller transfers a defined volume of printing fluid onto a flexible plate around the printing cylinder and from there directly onto the silicon wafer.*

The complete fabrication of front contacts by rotary printing processes and the application of rotary printing to transfer functional media is also the subject of current work. So-called flexography is a particularly suitable rotary printing process for front-surface metallization. It is a relief printing process, in which raised areas on a flexible plate around a printing cylinder transfer the printing fluid onto the silicon wafer. With this procedure, extremely fine finger structures (finger widths of 25 µm were demonstrated) can be produced with a high throughput. In addition, other rotary printing processes are being evaluated.



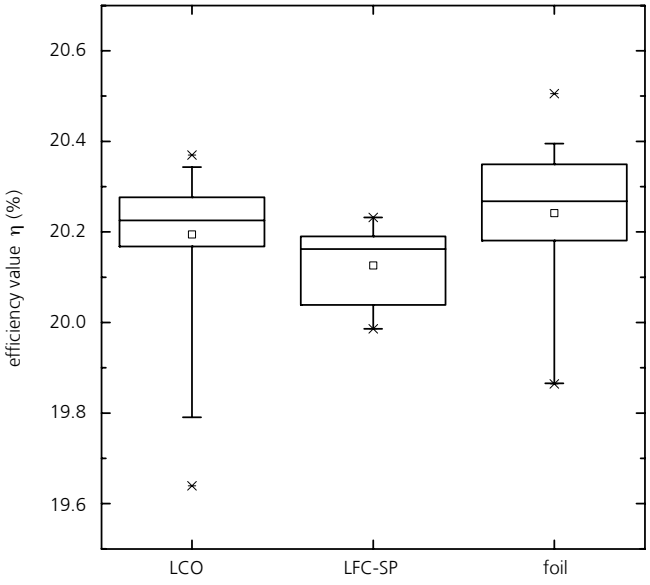
INNOVATIVE FOIL ELECTRODES FOR PASSIVATED SOLAR CELLS

Solar cells with passivated back surfaces can achieve higher efficiency values than conventional cells. This technology is thus being tested in pilot production plants around the world and has already been transferred to mass production in a few cases. However, additional processing steps, which interact sensitively with each other, make it complex and expensive, so that its cost advantage is slight, despite higher cell efficiency values. A technique that has been developed at Fraunhofer ISE, in which conventional aluminium foil is welded to the silicon wafer by laser radiation, simplifies the production of back-surface passivated cells significantly. It offers the potential for higher efficiency and is appreciably less expensive at the same time. This technology is being developed for series production in the "FolMet" project.

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

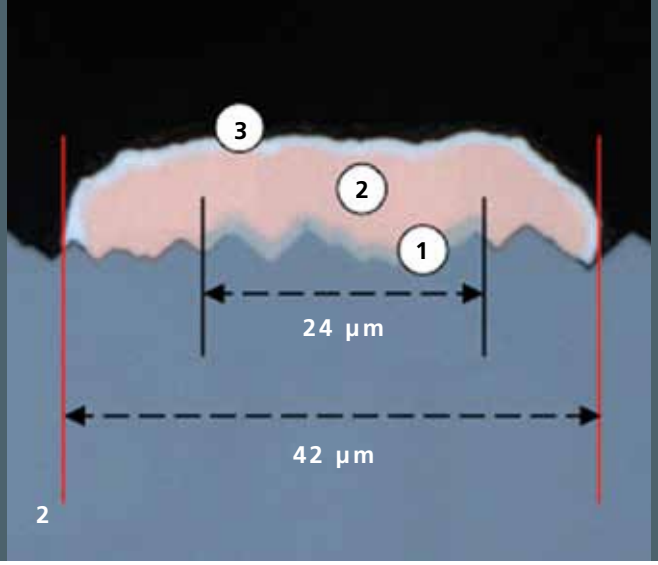
The application of conventional aluminium foil is a much gentler procedure than standard screen-printing to metallize the passivated back surface of solar cells. Single laser pulses are used to alloy it through the passivation layer and weld it with the silicon. These contact points create the mechanical and electrical connection between the foil electrode and the silicon base. The process makes cell short circuit currents feasible that are up to 0.3 mA/cm^2 higher due to improved optical properties. In addition, the series resistance is reduced, as it is possible to apply the metal closer to the edge of the wafer and the foil has better lateral conductivity. Apart from clearly increased cell efficiency, foil metallization also offers an appreciable cost advantage, as the material costs for the electrode are reduced by up to 90% and at least one individual processing step can be saved in comparison to the standard procedure. In the "FolMet" project, the improved efficiency potential compared to the reference has already been demonstrated successfully, with values up to 20.5%, as has the option for connecting cells with foil electrodes (Fig. 2).

1 *Dielectrically passivated back surface of a crystal silicon solar cell with its aluminium foil electrode.*



2 *Efficiency values of PERC solar cells produced by industrially relevant processes. The cell with a foil electrode presented here (foil) is compared with commercially established processes to produce local back contacts on the basis of screen-printed electrodes – LCO (local contact opening) and LFC-SP (laser fired contact, screen-printed). Each group of results is based on 15 to 41 solar cells which were produced from magnetically grown Cz silicon with identical front cell surfaces.*

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



SOLAR MODULES WITH CELL CONTACTS MADE OF NICKEL AND COPPER

Silver and lead are the two most critical materials in PV solar module construction, for cost and availability constraints or health concerns, respectively. At Fraunhofer ISE, a multi-step contacting process was developed to avoid using these materials. A first approach is based on currently used contacting technology and complemented by plating, already leading to drastically reduced silver consumption. In a second stage, silver and lead are eliminated completely from the front contacts, which are instead formed by nickel, copper and tin plating. We have now demonstrated both approaches successfully at the module level.

Jonas Bartsch, Gisela Cimiotti, Markus Glatthaar, Achim Kraft, Andreas Lorenz, Andrew Mondon, Stefan Glunz

Currently, screen printing of silver pastes is the standard technology to form the front contacts of silicon solar cells. Despite recently achieved reductions in consumption, silver used in solar cell front contacts is still an important cost driver in PV production. Replacing silver by more readily available and about 100x cheaper copper has the potential to reduce costs and susceptibility to price fluctuations. The efficiency potential is similar or even higher, as copper plating allows the formation of very compact and highly conductive contacts.

At Fraunhofer ISE, plating of nickel and copper on fine-line, screen-printed seed layers and directly on silicon are approaches to replace silver by copper. Contact adhesion has been one of the most challenging issues to tackle. In that respect, breakthroughs have been achieved very recently in cooperation with our partners. These developments allowed the construction of two prototype modules with the above mentioned techniques using standard soldering for interconnection. All adhesion criteria have been exceeded.

1 *Solar module featuring solar cells with fine-line, screen-printed seed layer plated with nickel, copper and silver, in front of copper-plating facility at Fraunhofer ISE.*

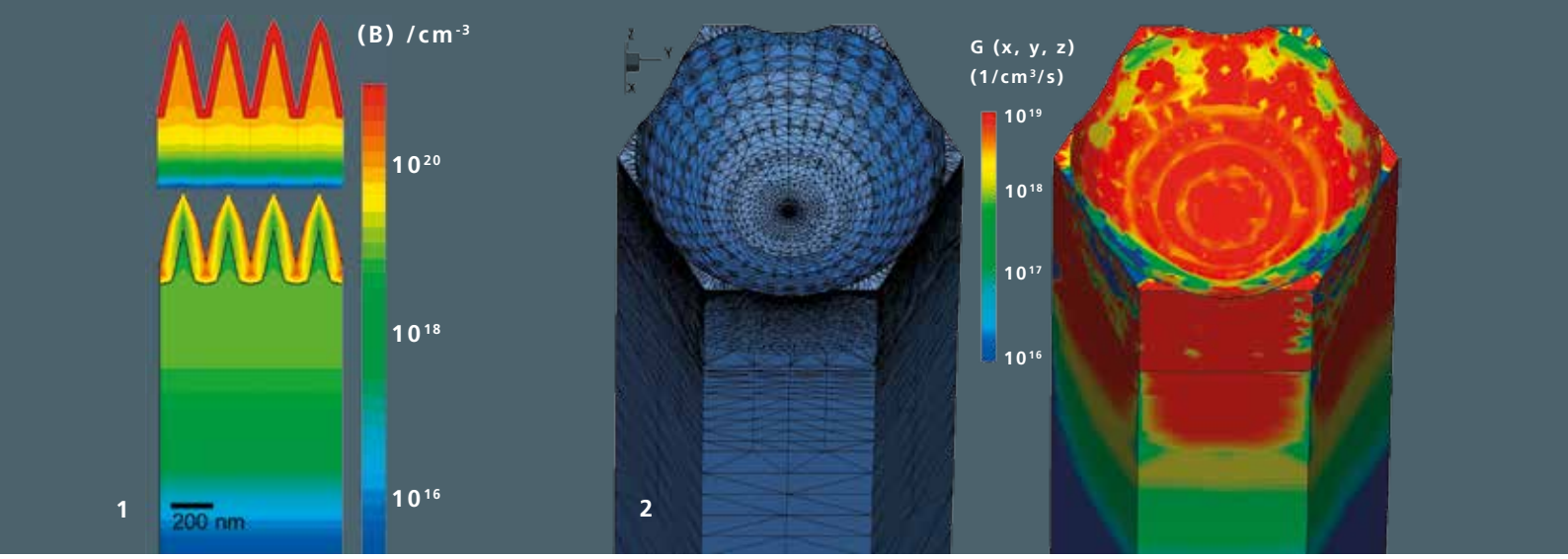
2 *Cross-section through fully plated contact consisting of nickel (1), copper (2) and tin (3).*

The first module features cells with easy-to-implement plating of nickel, copper and silver on fine-line, screen-printed contacts. Silver consumption was reduced from approx. 120–150 mg to 13 mg per cell for metallization by an improved screen-printing process (only 15 mg laydown of wet paste with low Ag content).

For the second module, direct plating of nickel enables cells with completely silver-free and lead-free front contact architecture. A detailed understanding of the Ni-Si solid state reactions enabled us to develop well-adhering contacts. These are comparable to high-efficiency contacts for laboratory solar cells or integrated circuits, at low cost and industrial feasibility. This makes them promising candidates for next-generation solar cell concepts, such as n-type cells.

With these results, such cost-saving metallization processes can be adapted by a multitude of manufacturers with relatively little effort. Based on our experience, Fraunhofer ISE can offer support with these processes, together with our partners.

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



SIMULATION MODELS FOR HIGH-EFFICIENCY SOLAR CELL CONCEPTS

Highly efficient solar cells feature increasingly complex structures. At the same time, the optimisation of individual processing steps strongly influences the solar cell efficiency. In order to limit the number of time-consuming experiments when developing new solar cell concepts, predictive simulation is thus becoming increasingly important. Multi-dimensional semiconductor simulations to quantify optical and electrical solar cell properties and predict dopant distributions are important components of this process.

Martin Bivour, Johannes Greulich, Martin Hermle, Stefan Rein, Marc Rüdiger, **Jonas Schön**, Sebastian Schröer, Heiko Steinkemper, Wilhelm Warta, Nico Wöhrle, Ralf Preu, Stefan Glunz

Numerical simulations are applied specifically to enhance understanding of the physical processes in solar cells. Combined with extensive parameter variation, simulation studies enable very focussed solar cell development. The simulation tools and models, which have been further developed and continually improved over the years, have become increasingly accurate in their predictions of real solar cell performance, allowing technological developments to reach commercial maturity more rapidly.

The extension and calibration of diffusion, precipitation and implantation models for boron and phosphorus by dopant profile measurements allow single and multi-step doping processes to be predicted accurately. For instance, simulation of boron implantation and the subsequent high-temperature annealing step, which takes the formation and solution of boron precipitates into account, was used to develop novel implantation processes to create emitters in solar cells

1 Simulation of a boron emitter on a silicon wafer with a "black silicon" texture after a BBr_3 doping process with (below) and without (above) additional oxidation.

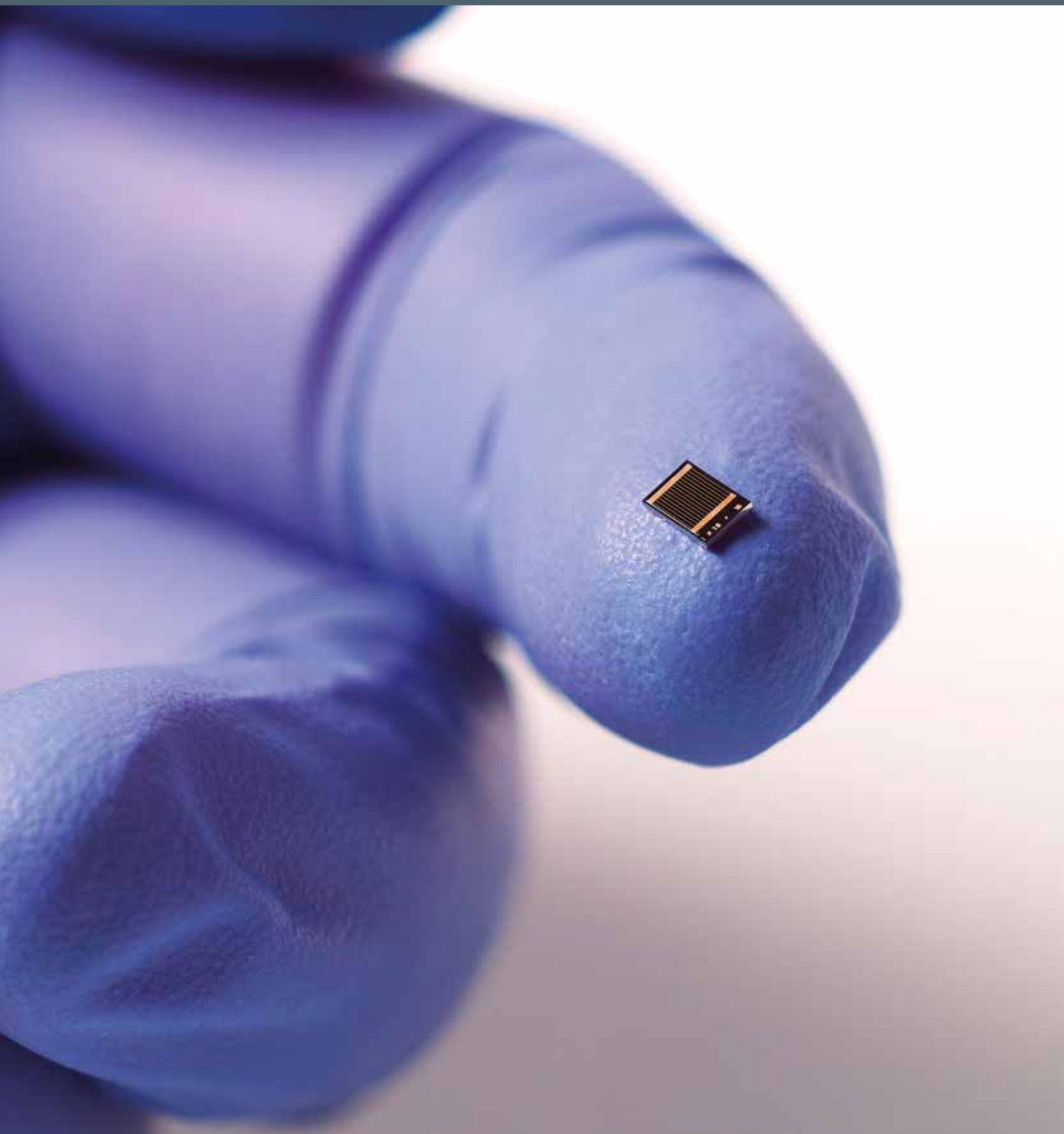
2 Symmetry element and grid (left) and simulated optical generation rates (right) for monochromatic illumination (λ = 0.7 µm) with an intensity of 0.1 W/cm², for a cell with honeycomb texture.

based on n-type silicon. Among other effects, the growth of borosilicate glass and silicon oxide was considered in the simulation of boron diffusion in "black silicon" – silicon with a needle-textured surface and thus excellent optical properties (Fig. 1).

With respect to optical properties, simulation models help to evaluate the development potential of different textures and to optimise them further. For example, three-dimensional simulation of so-called honeycomb structures allowed the improved light trapping by these novel front-surface textures to be quantified (Fig. 2).

Highly efficient amorphous / crystalline hetero-structure silicon solar cells have an effectively one-dimensional structure which can thus be simulated with 1D models. However, there is strong interaction between the individual layers and a description of charge carrier transport across the individual layer boundaries with classic transport models proves to be inadequate. It is only when quantum mechanical tunnelling mechanisms between the TCO (transparent conductive oxide) and the doped a-Si layers are taken into account that the very strong influence of doping efficiency of the a-Si layer and the work function of the TCO on the IV characteristic curve for the solar cell is described correctly. On this basis, conclusions can then be drawn to optimise the layers.

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 today almost 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 the terrestrial application of concentrator solar cells in highly concentrating photovoltaic systems, research approaches are determined by the goals of high efficiency and reduced costs for production processes. The market for terrestrial, high-concentration photovoltaics has been expanding for years. A decisive contribution to this development has been made by Concentrix Solar – now Soitec Solar – a spin-off of Fraunhofer ISE from 2005.

In order to achieve higher efficiency and lower costs, we optimise processing technology, develop materials and develop 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 and sextuple solar cells. We are working with strain-compensated multi-quantum wells to improve the current matching in multi-junction solar cells. For metamorphic growth concepts, where material with different lattice constants is 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.

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. In October 2013, we achieved the world record efficiency value of 44.7% with a wafer-bonded quadruple solar cell. The record cell was developed jointly with our partners Soitec, CEA-Leti and the Helmholtz Centre in Berlin (page 49).

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 photovoltaic cell is used in wireless power supply systems (page 52).

In order to use III-V multi-junction solar cells also in terrestrial applications, we develop highly concentrating photovoltaic 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 (page 51). The FLATCON® module which we developed is an example for this approach. We continue to optimise it further to achieve higher efficiency and lower manufacturing costs. In ConTEC (Concentrator Technology and Evaluation Centre), we investigate module production processes and reliability. We offer our expertise in thermal, optical and electrical simulation to the benefit of clients. We optimise and develop processes and innovative systems.

In addition to high-concentration photovoltaics based on III-V multi-junction solar cells, we also work on low-concentration systems (page 50). These cover the concentration range from a factor of 2 to 30. We cooperate with clients in developing optical concentrators, mounting solar cells and designing and measuring systems. For application in low-concentration systems, we have developed special Si solar cells. In PV-TEC (Photovoltaic Technology Evaluation Centre), series for special applications can be produced for clients.

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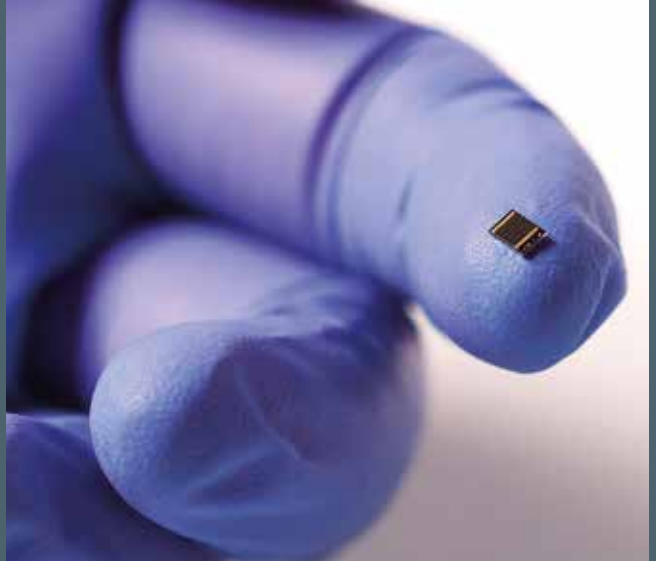

World record solar cell with an efficiency value of 44.7% (@297xAM1.5d), consisting of four sub-cells based on III-V semiconductors, for application in concentrator photovoltaics.

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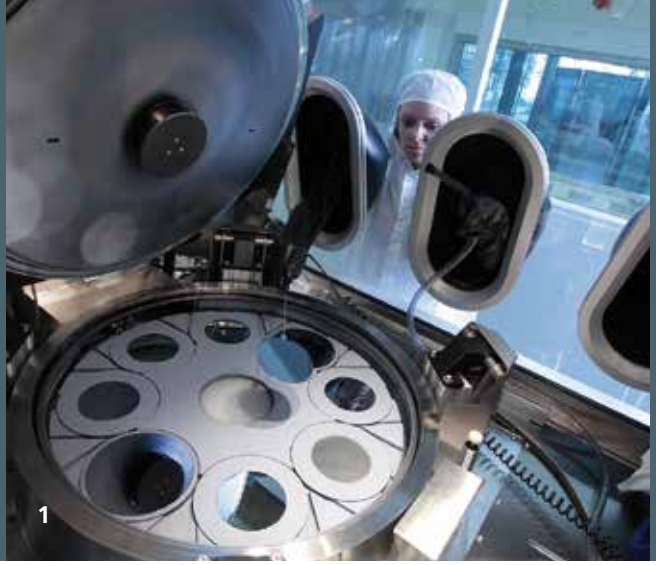


HIGH-EFFICIENCY, WAFER-BONDED, III-V MULTI-JUNCTION SOLAR CELLS

Electricity is one of the most valuable and useful forms of energy in our modern society. The higher the efficiency with which we generate this electricity from renewable energy sources, the smaller is the amount of land area and material which is required. Together with Soitec S.A. and research partners at the Helmholtz Centre in Berlin and CEA-Leti in Grenoble, we are developing technology for the most modern multi-junction solar cells and have achieved efficiency values of up to 44.7%. These special solar cells are used in highly concentrated sunlight, e.g. in the concentrator systems of Soitec.

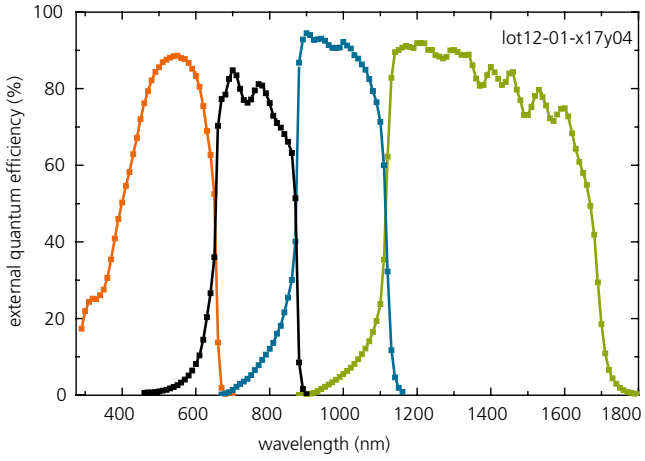
Paul Beutel, **Frank Dimroth**, Elvira Fehrenbacher, Ulrich Fiedeler, Matthias Grave, Christian Karcher, Karin Mayer, Eduard Oliva, Michael Schachtner, Manuela Scheer, Inessa Semke, Gerald Siefer, Thomas Tibbits, Katrin Wagner, Alexander Wekkeli, Andreas Bett

Multi-junction solar cells distribute incident sunlight over several sub-cells, which each absorb it in a different spectral range and convert it very efficiently into electricity. It is important to combine the best material properties in these high-performance solar cells. The expertise of Fraunhofer ISE is in the epitaxy of complex III-V compound semiconductor structures. Examples for these materials include gallium arsenide, gallium indium phosphide or indium gallium arsenide. We use the most modern epitaxial equipment with high throughput rates and develop industrially compatible processes to produce complex stacks of III-V layers.

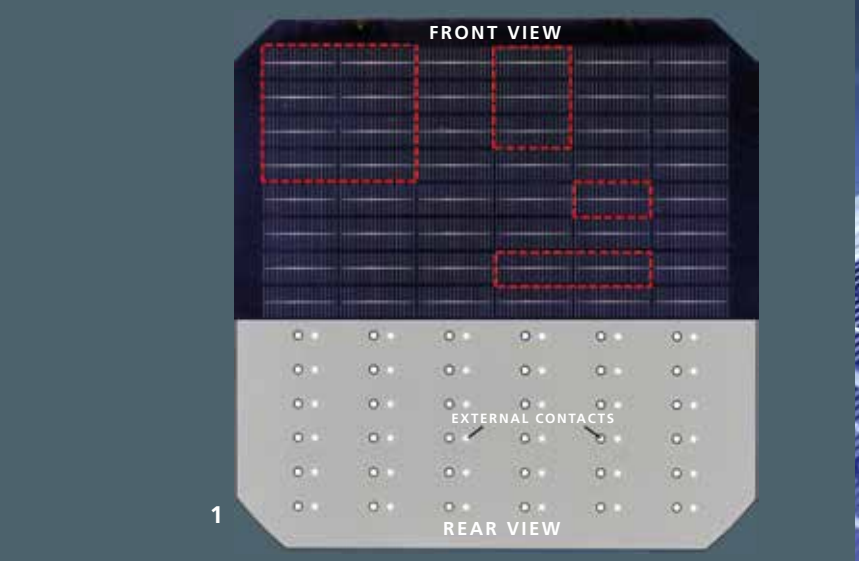
Crystals, which cannot be grown on top of each other due to their different lattice constants, are joined in a so-called "wafer-bonding" process by our project partners at CEA-Leti or Soitec. In this way, we were able to jointly prepare a quadruple-junction solar cell based on gallium arsenide and indium phosphide crystal structures, thus creating the most efficient solar cell in the world. This solar cell achieves an efficiency value of 44.7% for 297x concentrated sunlight (Fig. 3).

1 *III-V semiconductor films for solar cells are deposited in an epitaxial reactor.*

2 *Hundreds of small quadruple-junction cells made of GaInP/GaAs//GaInAsP/GaInAs are processed on a single substrate and subsequently used in photovoltaic concentrator modules.*



3 *External quantum efficiency of the developed quadruple-junction solar cell with an efficiency value of 44.7%.*



LOW-CONCENTRATING PV – LCPV: Si SOLAR CELLS AND RECEIVERS

In LCPV systems, silicon solar cells which have been modified for the relevant irradiation conditions are used. We develop back-contacted Si solar cells, which suffer less shading loss due to the front contact grid. In this way, we achieve efficiency values of up to 21% for 15x concentrated solar radiation. In addition, we conduct research on the integration and connection of solar cells in receivers and the design and preparation of optics to concentrate solar radiation. We thus offer complete system solutions or system integration.

Daniel Biro, Florian Clement, Matthieu Ebert, Ulrich Eitner, Tobias Fellmeth, **Ingrid Hädrich, Maike Wiesenfarth**, Andreas Bett, Ralf Preu, Harry Wirth

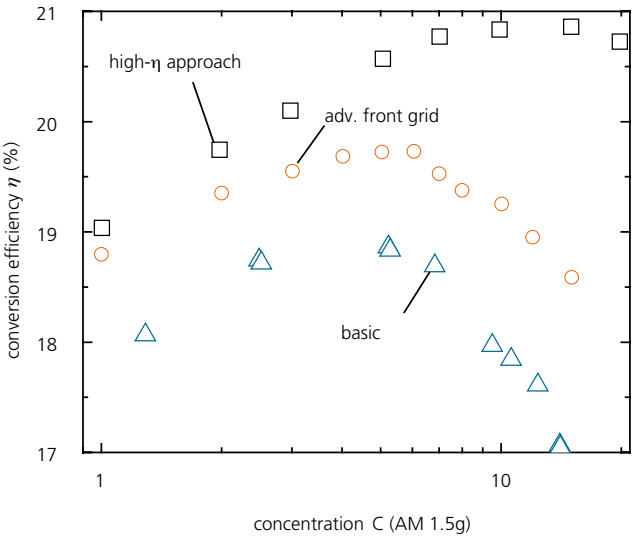
LCPV systems generate electricity cost-effectively, using adapted silicon solar cells. A concentrator system consists of concentrator optics and the receiver, in which the solar cells are connected and encapsulated such that they achieve high electric efficiency, good thermal conductivity and adequate protection against environmental effects. The system design can vary, e.g. reflective or lens-based optics of different sizes are used, which then track the sun in single-axis or dual-axis systems. The components must be carefully matched to each other in each system design. For low concentration factors of 2 to 30, we have developed a flexible, modular solar cell design for an industrially manufactured "metal wrap-through" (MWT) Si solar cell (Fig. 1). This allows us to adapt the size of the solar cell quickly to individual systems and yet still apply unified characterization and connection procedures.

1 Wafer with several MWT solar cells (top – front, bottom – back). The modular design allows special configurations of solar cells to be used, which consist of multiples of the unit cell (1 x 2.25 cm²) (examples within red outlines).

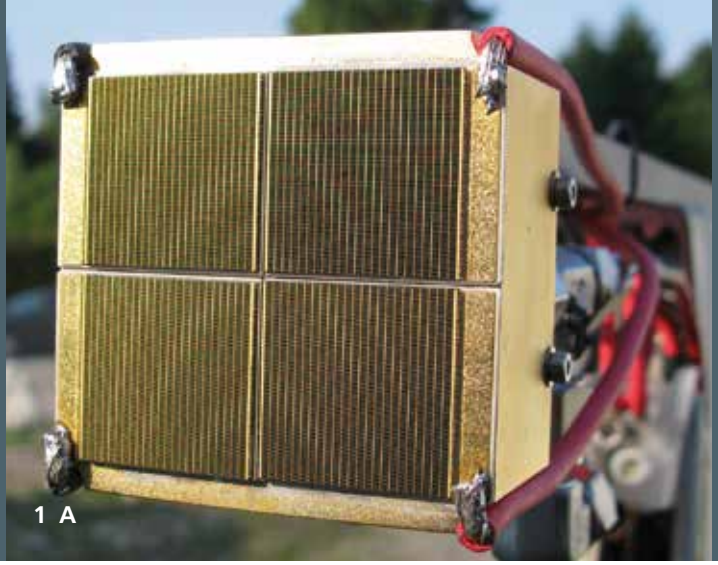
2 Receiver with electrically connected and encapsulated MWT solar cells.

Fig. 2 shows a receiver which can be used, among other applications, in a parabolic trough with a concentration factor of up to 25. For this development, we profit from our experience with PV flat-panel module technology and high-concentration module technology. As far as possible, we apply standard production processes from these technologies and adapt them for the production of prototypes and small series.

In doing so, we pursue several different technological approaches. On the one hand, we aim to achieve more cost-efficient processes (base). On the other hand, we are implementing more complex processes for the front surface and the application of high-quality Si substrates (high efficiency), leading to higher efficiency values (Fig. 3).



3 Efficiency values of Si solar cell versus concentration factor for different cell technologies.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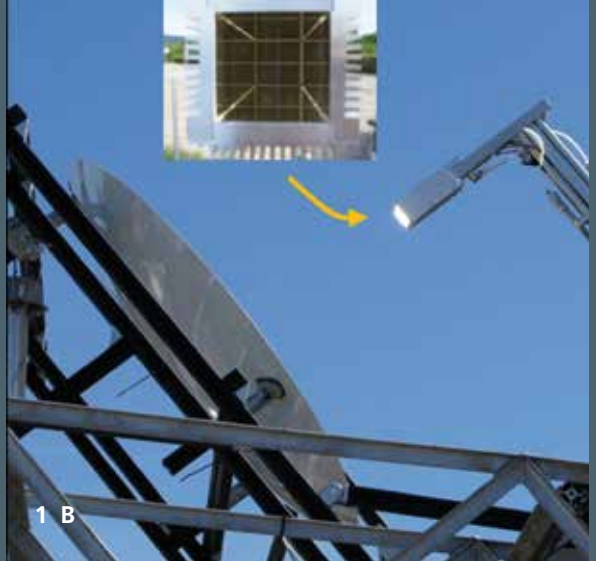

1 B

CONCENTRATOR PV AND THERMAL (CPVT) SYSTEM AND RECEIVER DEVELOPMENT

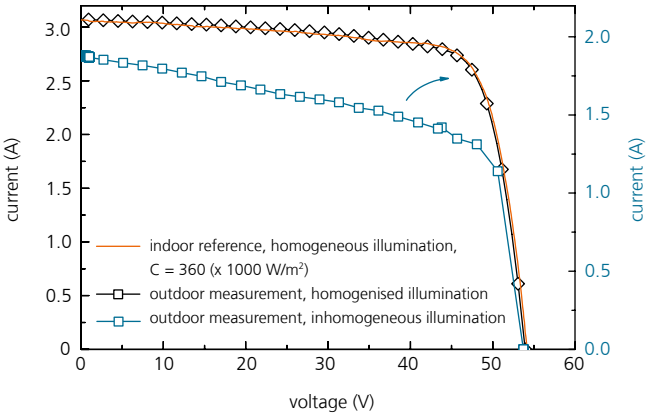
CPVT systems generate not only electricity but also heat, so that sunlight in such systems is converted with an efficiency of up to 80%. Actively cooled solar cell modules are a pre-requisite for CPVT systems with high concentration factors. We develop different configurations for these modules and implement secondary optics to distribute the concentrated sunlight homogeneously. These prototypes are then analysed under real operating conditions.

Armin Bösch, Alexander Dilger, Tobias Dörsam, Sebastian Gamisch, Henning Helmers, Wei Yi Thor, **Maike Wiesenfarth**, Andreas Bett

Not only lens-based optics but also reflective optical systems are used in highly concentrating systems. When parabolic reflector systems with an area of several square metres are used, the solar cells must be actively cooled. Thus, the thermal energy can also be used in addition to the generated electricity. In this type of so-called CPVT system, the solar energy is converted with an efficiency value of up to 80%.

The challenge associated with such systems is presented by the design of the solar energy receiver, the Compact Concentrator Module (CCM). Here, we place many solar cells with an area of 1 to 5 cm² with a high packing density on a cooling body. In developing such CCMs, we concentrate on the production technology, the integration of bypass diodes, new encapsulation methods, long-term stability and new cell structures for highly efficient, large-area solar cells. We test and analyse our various CCMs under real outdoor conditions in our outdoor test stand. Homogeneous illumination of the entire module area is necessary when the solar cells are connected in series. To this purpose, we have developed optics which homogenises the spatial distribution of the illumination. The measurement result in Fig. 2 shows that the losses due to spillover and inhomogeneous electricity generation by the series-connected solar cells are avoided by use of the homogeniser.

1 *Compact concentrator modules (CCM), developed and investigated by Fraunhofer ISE for use in CPVT systems: CCM with an alternative cooler design and four MIM solar cells, each with an area of 4.4 cm² (MIM – monolithically interconnected module) (A); CCM with secondary optics mounted on our outdoor test stand (B).*



2 *Current-voltage characteristics of a concentrator module with a reflective system under homogeneous illumination indoors, outdoors with "homogenising" optics and outdoors without the homogenising component. In contrast to homogeneous illumination, inhomogeneous illumination causes losses due to spillover beyond the edges of the receiver and mismatch losses in the fill factor due to the series connection of solar cells on the receiver.*

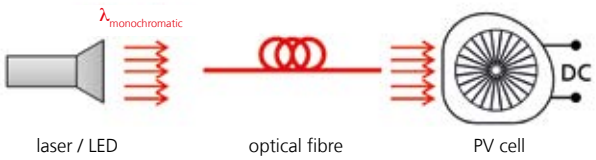
The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

PHOTOVOLTAIC CELLS FOR OPTICAL POWER TRANSMISSION

Supplying power to electronic devices via copper or coaxial cables can cause problems in certain environments. This includes applications in which very good electric or magnetic isolation is necessary to prevent sparks, short circuits or electromagnetic disturbance. Rotating systems or inaccessible locations also present difficulties. Optical power transmission offers an alternative in such situations. It requires three essential components (Fig. 3): A monochromatic radiation source (laser or LED), a transmission medium (air or optical fibre) and an energy converter (photovoltaic cell).

Henning Helmers, Eduard Oliva, **Simon Philipps**, Kasimir Reichmuth, Dirk Reinwand, Gerald Siefer, Andreas Bett

Photovoltaic cells made of III-V semiconductors can convert monochromatic light very efficiently into electricity. The key to achieving high efficiency values is matching the wavelength of the incident light and the band gap of the photovoltaic cell. With GaAs-based cells and laser power transmission, we have already achieved efficiency values of up to 54.9%, measured with a laser wavelength of 810 nm.



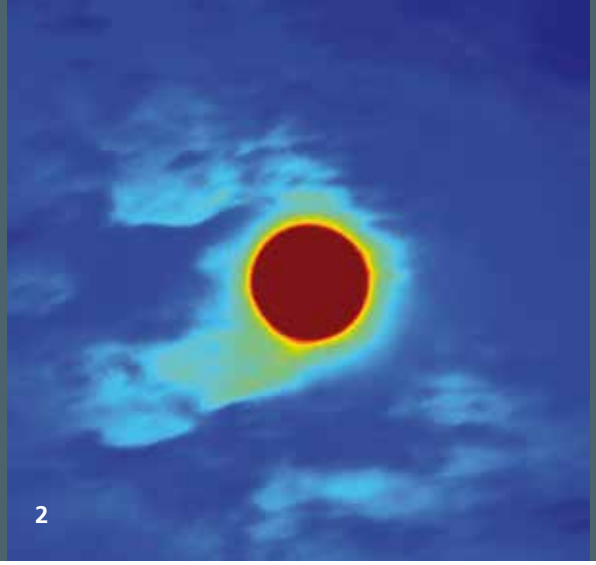
3 *Schematic configuration of a system for optical energy transmission. A laser serves as the optical energy source; its monochromatic radiation is transmitted via an optical fibre onto a photovoltaic cell. This converts the optical energy with high efficiency into electricity.*

1 *Photovoltaic cell of GaAs to convert monochromatic radiation with a wavelength of 810 nm. The cell is mounted on a standard TO header for its integration into optical energy transmission systems. The cell consists of two integrated, serially connected segments, to achieve a higher output voltage.*

2 *Wire bonder to connect the photovoltaic cell on the standard mount. Our production line makes assembly with a high throughput and reproducible quality feasible.*

The diverse application areas for optical energy transmission lead to different requirements for the photovoltaic cells. In the currently running "Optowind" project, a lightning-proof sensor concept is being developed for technical monitoring and evaluation of wind-energy systems. The voltage of a conventional photovoltaic cell is not high enough for the power supply of the electronic components. We are thus developing photovoltaic cells with a higher output voltage. This is achieved by an integrated serial connection of several cells in a single component either by vertical stacking or by lateral connection (Fig. 1). In order to reduce attenuation in the optical fibres, it is also interesting to use lasers with longer wavelengths. Photovoltaic cells of GaInAs are being developed for the project which can efficiently convert radiation from powerful lasers with a longer wavelength of 980 nm.

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



HIGH-RESOLUTION SYSTEM TO MEASURE CIRCUMSOLAR RADIATION

The circumsolar radiation is that fraction of the incident solar radiation which is scattered by the atmosphere and thus reaches the earth from an angular zone around the solar disc. This fraction can be significantly high at locations in the desert or near the coast. Its exact angular distribution has a large influence on the efficiency value of highly concentrating photovoltaic systems. We have developed a new, camera-based measurement system, which records the angular distribution of the circumsolar radiation in the relevant range, its total intensity and its daily variation with high spatial resolution. The results of the measurements allow us to better understand the influence of the circumsolar radiation on the power yield of concentrating photovoltaic systems.

Thorsten Hornung, Peter Nitz, **Thomas Schmidt**,
Simeon Schrott, Maike Wiesenfarth, Andreas Bett

1 *The camera for time series of angle-resolved measurements of the circumsolar radiation (white housing) mounted on a support system which tracks the sun.*

2 *False-colour plot of an HDR image (High Dynamic Range Image) of the direct solar and circumsolar radiation, recorded with the measurement system. The irradiance decreases from dark red through yellow to dark blue over five orders of magnitude. Slight turbidity of the atmosphere is also visible.*

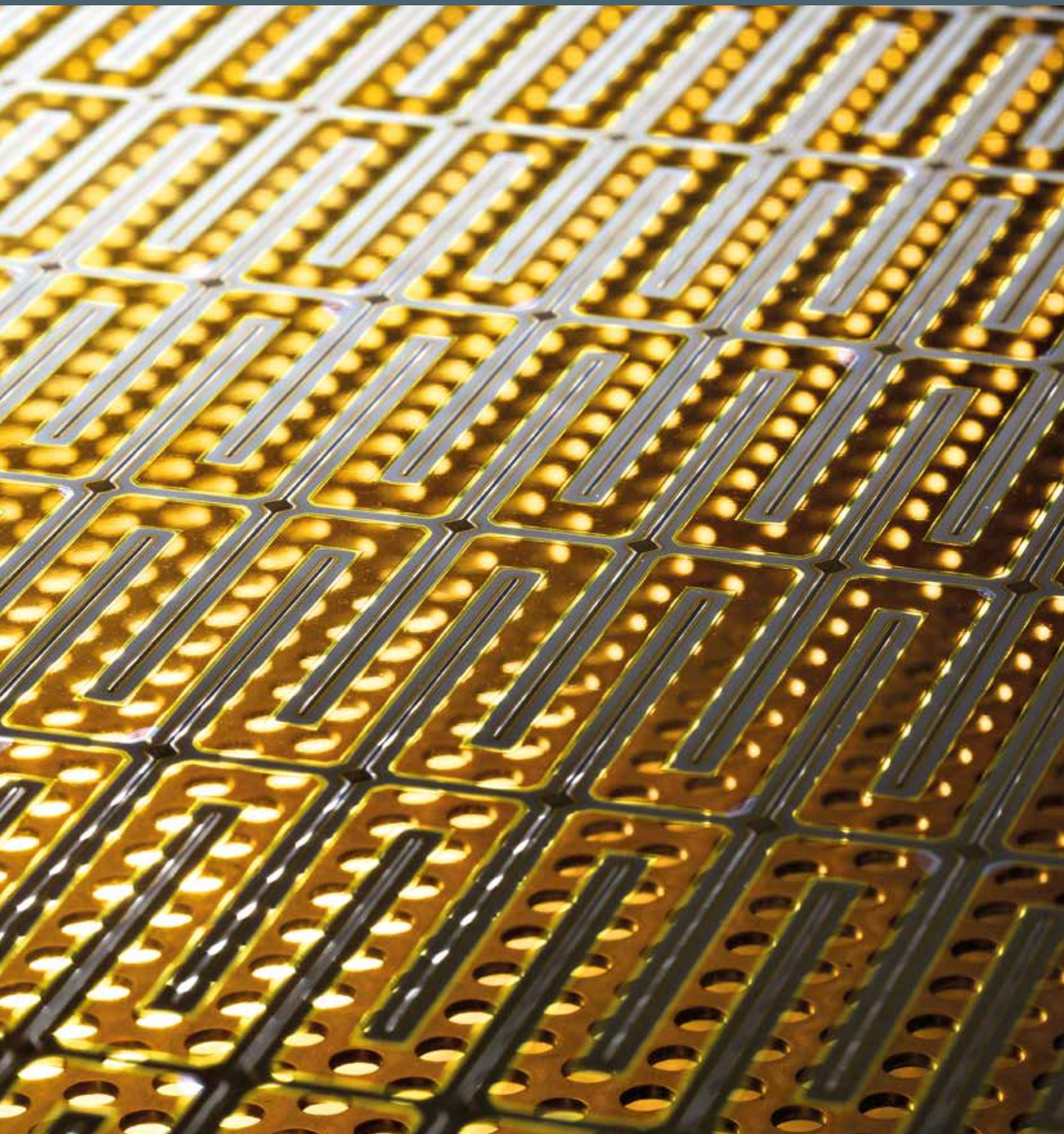
The measurement system (Fig. 1) consists of a camera and a lens system which was developed especially for this application. We optimised this in complex ray-tracing computer calculations and laboratory experiments with a solar simulator to minimise the scattered light. With the high-resolution camera system, we make up to 360 measurements and data analyses per hour. The distribution of the direct solar radiation is recorded two-dimensionally over an angular range up to a half-angle of 55 mrad with a resolution of 0.1 mrad. From these measured data, we calculate the circumsolar ratio (CSR) of the sunlight, among other quantities.

The irradiance values within and beyond the solar disc differ by up to five orders of magnitude. This difference greatly exceeds the dynamic range of the camera used. To enable accurate measurements despite this limitation, we adapted the high dynamic range (HDR) principle from photography. For the measurement, we combine four images which are exposed for different periods and calculate a single image from these. This method results in correct values for both the solar disc region and the much darker area around the sun (Fig. 2).

With this system, we can also measure high-resolution spectral distribution functions of the circumsolar radiation for the first time. On the basis of this data, we can understand the influence of circumsolar radiation on the energy yield of concentrating photovoltaic systems significantly better.

The project is supported by our industrial partner, Soitec Solar, and the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB).

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
- tandem solar cells on crystalline silicon

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 optimised 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 analyse 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 optimise different module structures for specific applications. In the laboratory, novel cell and module concepts with a high potential for cost reduction 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 thermalisation losses), we are also developing silicon-based tandem solar cells. In addition to process adaptation for the Si base 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. The two sub-cells are combined either by direct stack growth on the Si base cell or by wafer-bonding.

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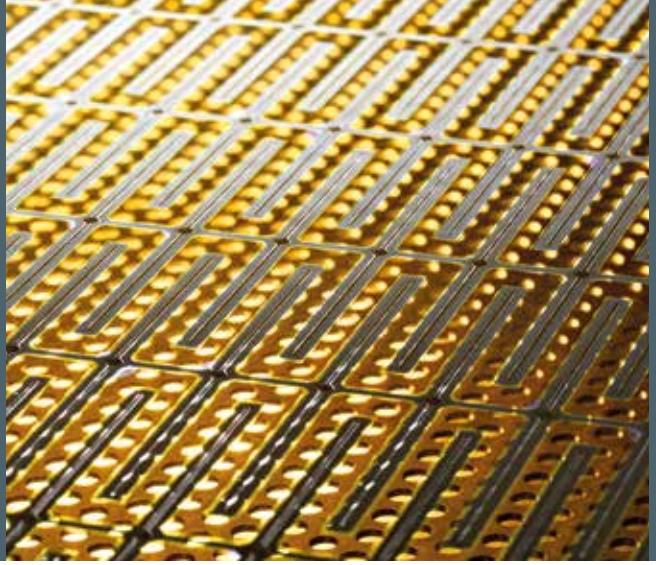

Detail from the production of a dye solar module sealed with glass frit.

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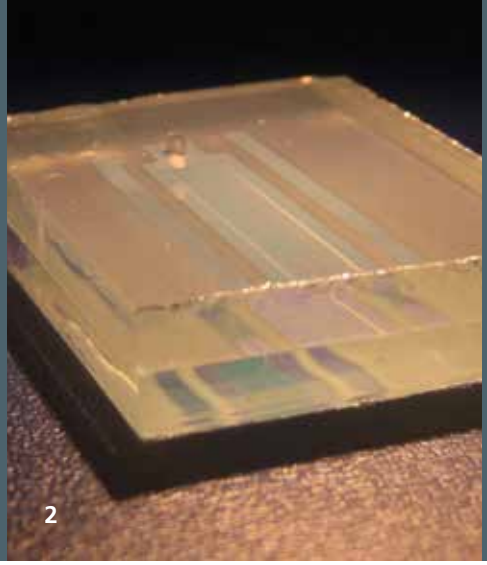
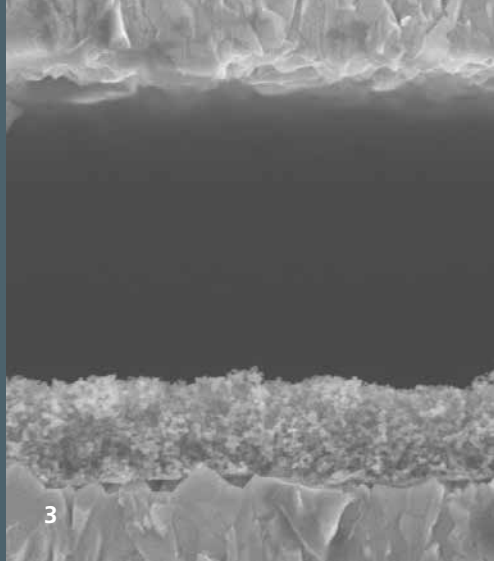




CONCEPTS FOR IN SITU PRODUCTION OF PEROVSKITE SOLAR CELLS

Over the past years, large-area dye solar modules on glass substrates have been successfully developed at Fraunhofer ISE and the associated in situ production method established. The solar cells are fabricated from solutions within a module that is hermetically sealed by low-melting glass frits; vacuum processes and module lamination steps are not required. As our conceptual work in 2013 demonstrates, this cost-effective technology can be transferred very well to the emerging research field of perovskite solar cells.

1 *In situ production of solvent-based solar cells; already implemented for dye solar modules.*

2 *Cross-section of a perovskite solar cell configuration sealed with glass frit.*

3 *Cross-sectional scanning electron micrograph of the cell configuration before filling.*

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

Perovskite solar cells are still at the stage of university research. However, after a certified laboratory efficiency value of 14.1% was attained in 2013 by perovskite solar cells that had been deposited from solution, this concept has attracted strong research interest around the world. A further increase in efficiency is anticipated as the underlying photovoltaic principles become better understood. Parallel to fundamental research, it is now necessary to develop suitable concepts for upscaling the cells in a cost-effective process.

Starting from the glass frit procedure developed to seal dye solar cells, research is being conducted at Fraunhofer ISE on optimising and upscaling the principle of perovskite solar cells by an in situ coating method. Very thin (< 1 µm), porous substrate films are deposited by screen-printing onto two TCO-coated (SnO_2:F) glass substrates and thermally sealed with glass frit with a very narrow gap. A process was developed, in which the porous substrate films can be filled in sequence with the dissolved active material of the perovskite solar cell. By varying the porosity and the particle size in the substrate films, the active materials are deposited in a self-organised process by capillary forces, and form the solar cell after drying. Specially designed structures in the glass substrate make the transport and inert drying of the solvent feasible. The procedure enables future perovskite solar modules to be produced with minimal consumption of resources.

The work was carried out within the EU-funded "GLOBASOL" research project.

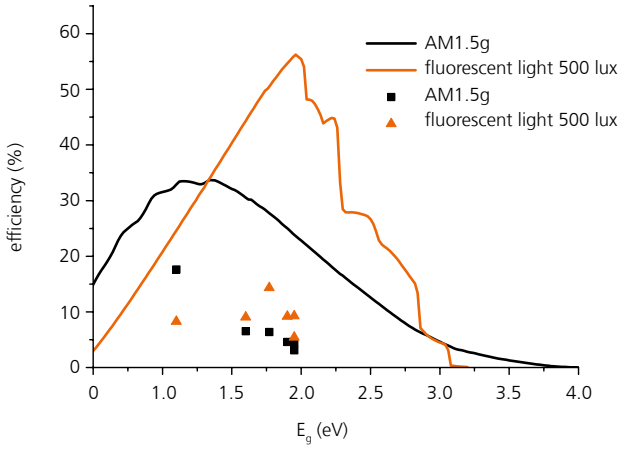
PRODUCTION AND APPLICATION POTENTIAL OF ORGANIC SOLAR CELLS

Organic solar cells have great medium-term potential to provide cost-effective renewable energy. To achieve this, the efficiency value must be further increased from currently about 10%, the long-term outdoor durability must be improved, and rapid and cost-effective roll-to-roll production must be further developed. Our work thus concentrates on cell and module concepts which are compatible with roll-to-roll production, on increasing the cell and module efficiency and improving long-term durability. Another focus is application-specific design and optimisation of cell and module concepts.

Deepak Kaduwal, Hans-Frieder Schleiermacher, Jan Schulz-Gericke, Clemens Veit, **Birger Zimmermann**, Uli Würfel, Stefan Glunz

1 *The organic semiconductor is deposited onto a metallised PET film by slot-die coating. Production rates of several metres per minute can be achieved with the laboratory facility at Fraunhofer ISE.*

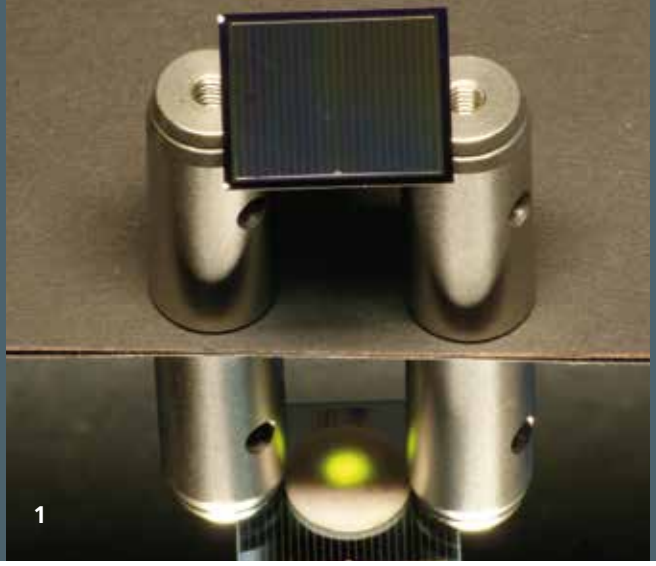
Organic solar cells with record efficiency values exceeding 10% are processed in the laboratory under an inert gas atmosphere by spin-coating with halogenated solvents. In this process, 90% of the material is wasted. The quantitatively reproducible and homogeneous application of the 100–200 nm thin semiconductor coatings is a great challenge to production technology. In order to save costs and improve the energy balance, processing in ambient air is highly favourable. In addition, hazardous solvents should be avoided to increase safety for production workers. We have developed a cell concept which allows processing in air from non-halogenated solvents and also uses very inexpensive materials and fabrication processes. With it, we produced solar cells with organic semiconductors that had been coated in a roll-to-roll process (Fig. 1), which achieved the same efficiency as in the laboratory process.

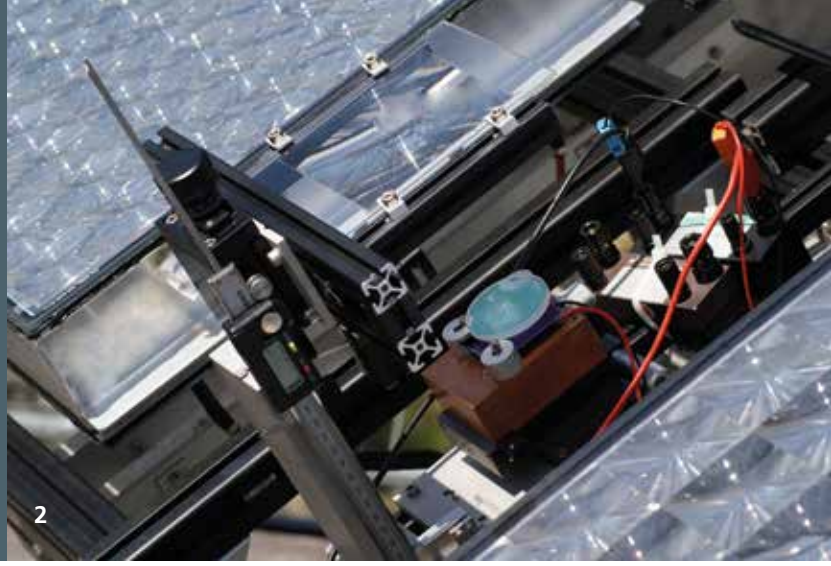


2 *Theoretical (lines) and measured (symbols) efficiency values of different solar cells under illumination by sunlight (black) and a compact fluorescent lamp (red) as a function of the band gap energy of the semiconductor.*

At their current stage of development, organic solar cells cannot yet compete with established photovoltaic technology. However, initial indoor applications are already conceivable, as organic solar cells achieve both high efficiency and promising long-term stability there. For example, sensors or display elements could have a power supply, without the need for installing cables or changing batteries. Under typical office lighting, we achieved an efficiency value exceeding 14% (Fig. 2).

The work was supported by the European Union and the Baden-Württemberg Foundation.





EXTRA CURRENT – USING MORE OF THE SUNLIGHT BY UPCONVERSION

Silicon solar cells cannot use about 20% of the energy contained in sunlight, because photons with energy lower than the band gap are not absorbed in silicon. Upconversion makes these lower-energy photons also useful. In this process, two photons with low energy are combined to generate one photon with higher energy. By improving the solar cells and materials used, a significant increase in current due to upconversion was measured for the first time at Fraunhofer ISE in concentrator modules with silicon solar cells and upconverters.

Johannes Eisenlohr, Stefan Fischer, Judith Frank, Benjamin Fröhlich, **Jan Christoph Goldschmidt**, Johannes Gutmann, Martin Hermle, Barbara Herter, Marc Rüdiger, Maike Wiesenfarth, Sebastian Wolf, Stefan Glunz

In an optimal system consisting of a solar cell and an upconverter behind it, it is necessary not only to absorb as much light as possible in the silicon (just as in a simple solar cell), but also as many low-energy photons as possible must pass through the solar cell to the upconverter. To this purpose, special bifacial silicon solar cells with a high efficiency value were developed at Fraunhofer ISE, which are ideally suited to further increase the efficiency by upconversion. They feature not only a double-layer anti-reflective front coating but also an anti-reflective coating of the back surface. This also ensures that the light emitted by the upconverter is coupled in well.

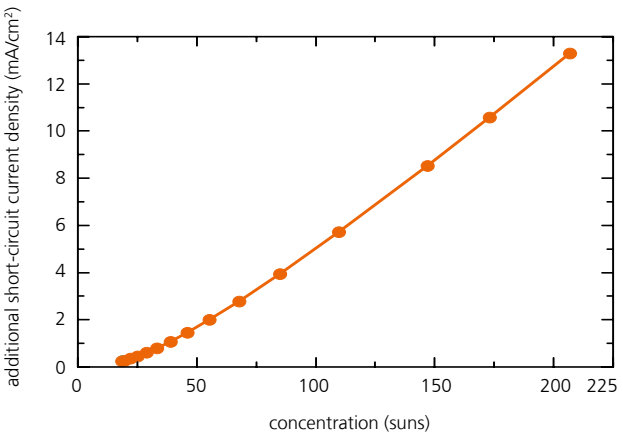
The upconverter on the back of the solar cell (Fig. 1) consists of erbium-doped sodium yttrium tetrafluoride, which was synthesised at the University of Berne. This microcrystalline powder was then encapsulated in a polymer by the Heriot-Watt University in Edinburgh.

1 *An invisible infrared laser is incident from above on a bifacial silicon solar cell and passes through it. Visible photons, which can be used by the solar cell, are generated by upconversion at the back of the solar cell.*

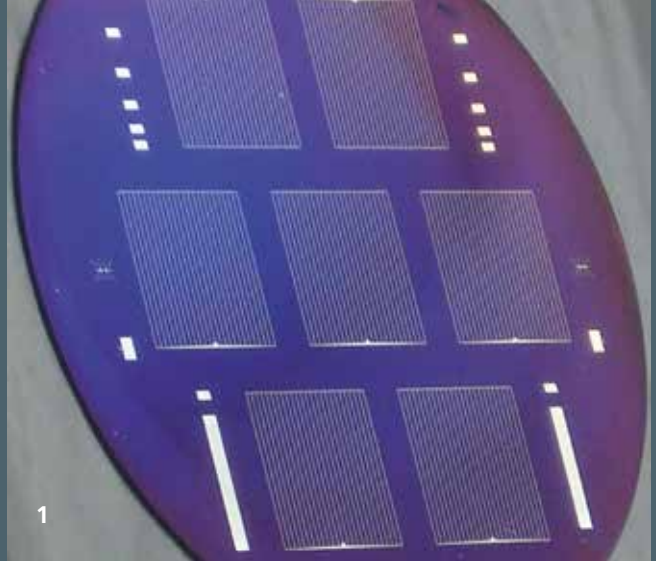
2 *Measurement set-up for a concentrator module with a silicon solar cell and upconverter.*

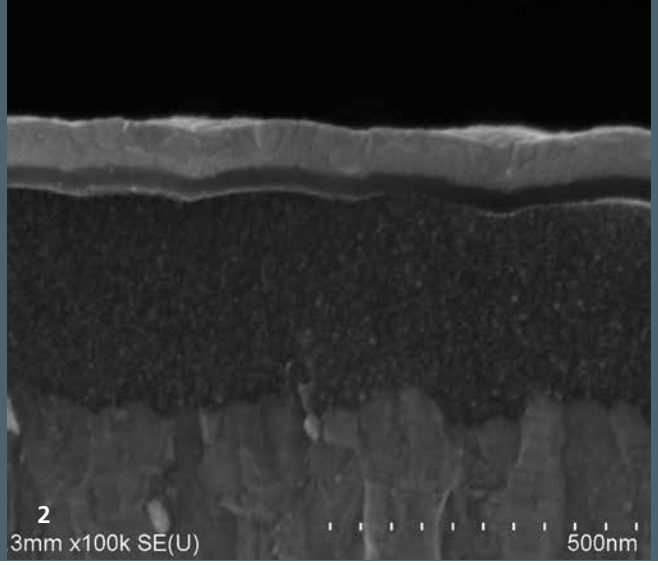
The system of upconverter and solar cell was integrated into a concentrator module (Fig. 2). The gain due to upconversion increases with the sunlight concentration factor (Fig. 3). Although the best results for upconversion to date were measured after the optimisation, the relative benefit for the solar cell is still slight. In order to change this, different photonic concepts are being investigated, with which the upconversion efficiency can be increased further.

The project was supported by the 7th framework programme of the European Union.



3 *Current gain due to upconversion versus the sunlight concentration factor.*





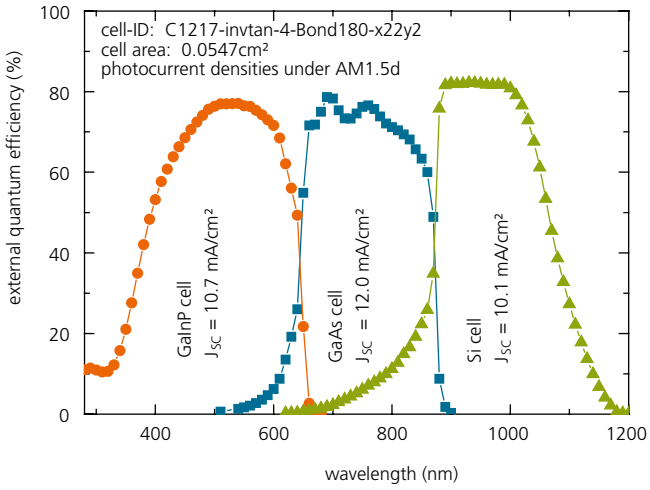
EXTREMELY EFFICIENT, TANDEM SOLAR CELLS ON CRYSTALLINE SILICON

Fraunhofer ISE is developing various concepts for solar cells based on crystalline silicon which aim to achieve efficiency values exceeding 25% for an intensity of one sun. One development focus is on tandem solar cells, in which absorbers with higher band gap energy are positioned above the base cell of crystalline Si. This combination of solar cells with different absorption characteristics allows the solar spectrum to be used much more efficiently, as thermalisation losses are reduced. We are investigating two main groups of materials as absorbers, III-V semiconductors and nano-crystalline Si.

Jan Benick, Frank Dimroth, Stephanie Essig, Jasmin Fuchs, Martin Hermle, **Stefan Janz**, Eduard Oliva, Dirk Reinwand, Andreas Bett, Stefan Glunz

1 *The very first tandem solar cell based on a c-Si bottom cell and a nanocrystalline Si top solar cell.*

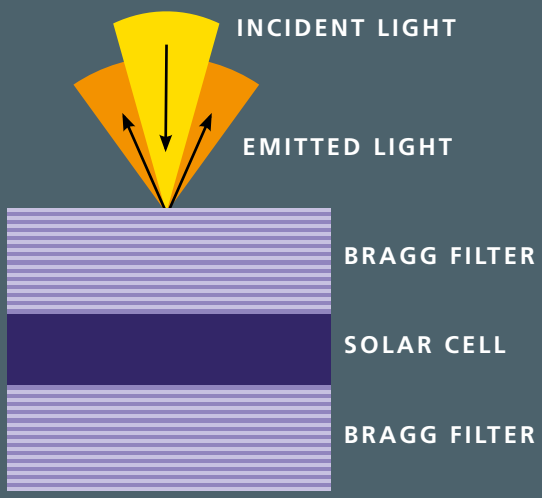
2 *Cross-sectional image of the tandem solar cell with the tunnel contact, the nanocrystalline Si absorber and the front contact layers.*



3 *External quantum efficiency of a GaInP/GaAs//Si triple solar cell. The photocurrent densities were calculated for each sub-cell at AM1.5d.*

Solar cells of III-V compound semiconductors achieve the highest efficiency today and are applied in space and in terrestrial concentrator systems. However, particularly due to the expensive substrates (GaAs, Ge), the cost of such cells is too high for flat-panel modules. At Fraunhofer ISE, we are working on combining III-V multi-junction solar cells with cost-effective Si substrates. Silicon is very well suited as the bottom sub-cell due to its absorption spectrum. "Wafer-bonding" is applied to bond silicon with further sub-cells of gallium arsenide (GaAs) and gallium indium phosphide (GaInP). In this way, an external quantum efficiency of more than 70% is achieved over a wide spectral range from 450 to 1035 nm (Fig. 3). Our triple solar cells achieve efficiency values of up to 24.4% under one sun and 27.9% under concentrated illumination. By improving the current matching between the sub-cells, we aim to increase the efficiency value to above 30%.

In cooperation with European research partners, the first exclusively c-Si-based tandem solar cell was produced at Fraunhofer ISE. The main development work consisted of adapting the Si wafer cell for the subsequent high thermal loads (solid-phase crystallization of the Si nanocrystals) and implementing a temperature-stable ohmic contact of crystal-line silicon carbide for the monolithic connection of the two individual cells. Achieving an open circuit voltage of 978 mV conclusively demonstrates the functionality of the solar cell assembly and its individual components.



1

PHOTONIC CONCEPTS FOR SOLAR CELLS IN THE RADIATIVE LIMIT

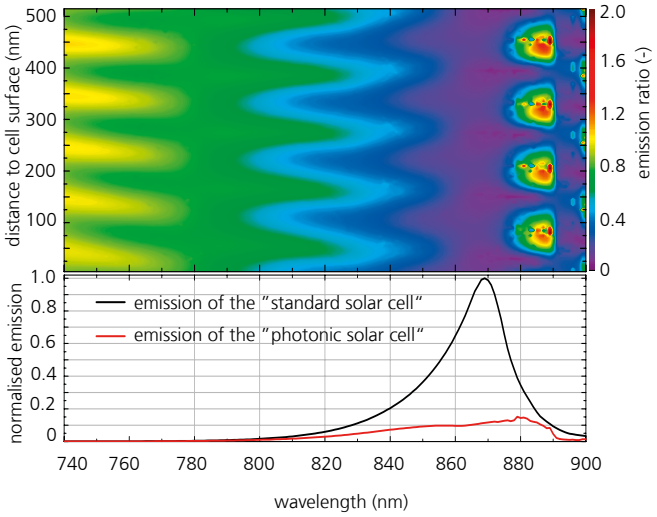
Thermodynamic losses occur due to the fact that the light incident on a solar cell originates only from a narrow angular region but the cell can emit into the complete hemisphere. To reduce these losses, we are developing angle-selective filters, which limit the emission and thus can increase the system efficiency. Designing and optimising suitable photonic thin-film filters is a challenge. We have developed programs which make this optimisation feasible and which allow the efficiency of such systems to be estimated on the basis of coupled optical and electrical properties. We are working on implementing such a system to provide experimental proof of the concept.

Benedikt Bläsi, **Oliver Höhn**, Tobias Kraus, Werner Platzer

Photonic thin-film filters can display angle-selective properties. One example is a Bragg filter, which consists of alternating layers of two materials with different refractive indices. At certain wavelengths, such filters have angle-dependent reflection peaks, which correspond very well to the requirements of a solar cell system. By cleverly modifying individual layer thicknesses and adding further layers, we further adapt this region and optimise the filter transmission in the range in which light falls on the cell. We apply a genetic algorithm to do so. The effect of such filters can be included in PC1D simulations, allowing the potential gain to be estimated.

A further-reaching approach is the introduction of a photonic solar cell, in which the cell and filter are combined in a single optoelectronic component. As an example, a thin GaAs solar cell can be introduced as a defect layer in a 1D photonic crystal (Fig. 1). In this case, in contrast to the effect discussed above, the emitted radiation is not reflected but the emission itself is suppressed (Fig. 2). To simulate this effect, we apply scattering matrix formalism. In addition, we couple these

1 *Schematic diagram of a photonic solar cell as a defect layer in a 1D photonic crystal. The emission angle of the cell can be narrowed in comparison to a "standard solar cell".*

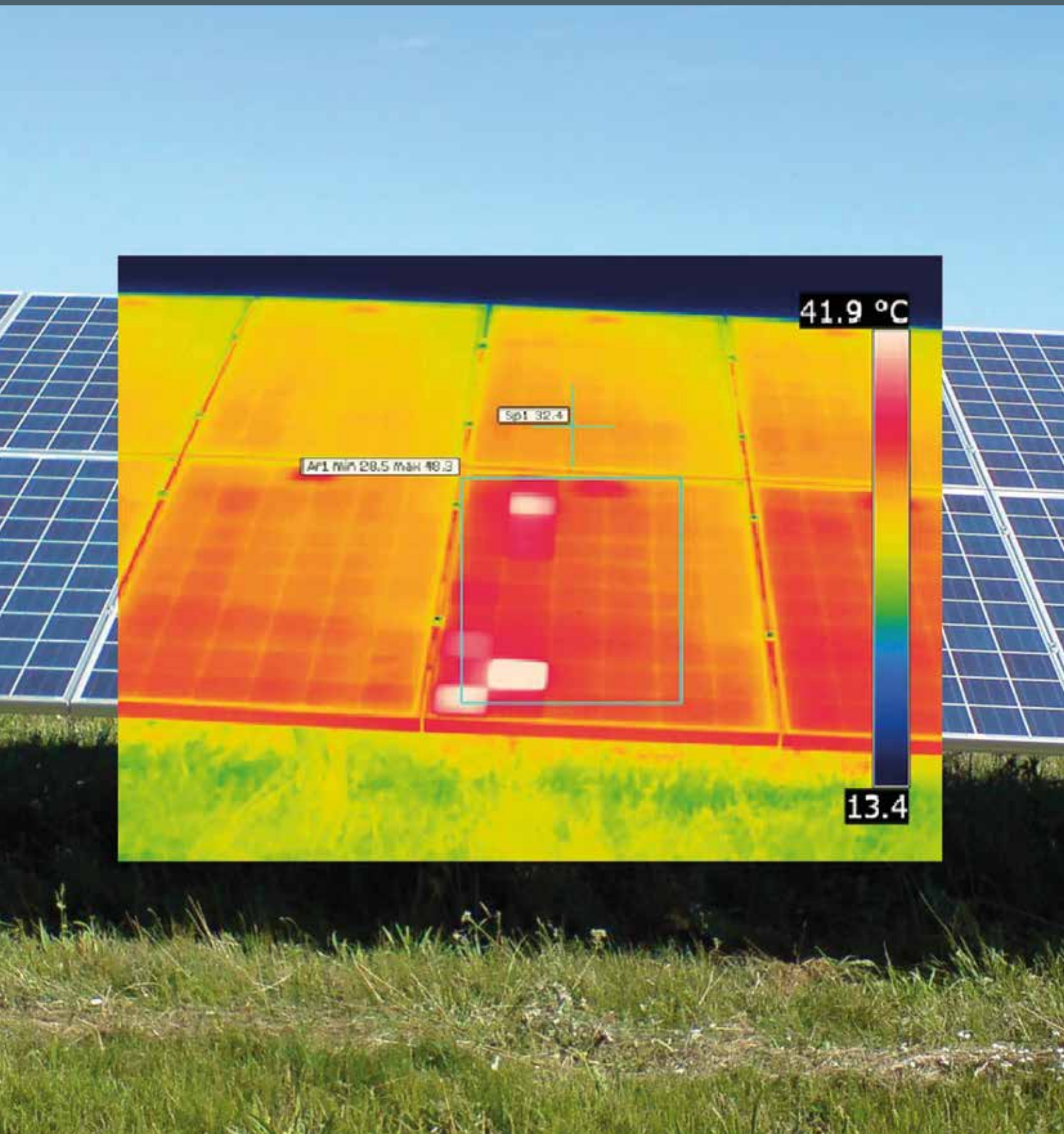


2 *Above: Ratio of the depth-dependent emission from the photonic solar cell to that from a "standard solar cell". Below: Total emission from a photonic solar cell in comparison to a "standard solar cell". The reduction in emission is evident.*

simulations with electric simulations (PC1D). Initial results show the desired suppression, so that we are now working on implementing such a system.

The work is supported within the "INFRAVOLT" joint project by the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB) and by scholarship programmes of the Deutschen Bundesstiftung Umwelt (German Federal Environmental Foundation).

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 specialised applications such as building integration. We characterize modules at the highest level of accuracy, analyse their service lifetime and offer comprehensive module testing. With accurate yield predictions, comprehensive system testing and exactly determined Performance Ratios during real operation, we ensure the quality of PV power plants.

The Photovoltaic Module Technology Centre (MTC) is equipped with a wide range of processing and analytical platforms for testing materials and developing products and processes for all stages of manufacturing. We apply simulations to analyse electrical, optical and mechanical effects in modules. Our scientists transfer developments from the laboratory phase directly to module pilot production in relevant sample numbers and formats.

In addition to the system efficiency, 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, in which the behaviour of test objects such as PV modules is observed and documented in detail in the field at selected locations. With our non-destructive analytical methods, we investigate the effect of climatic loads in order to identify aging mechanisms as early as possible, e.g. by Raman and infrared spectroscopy.

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.

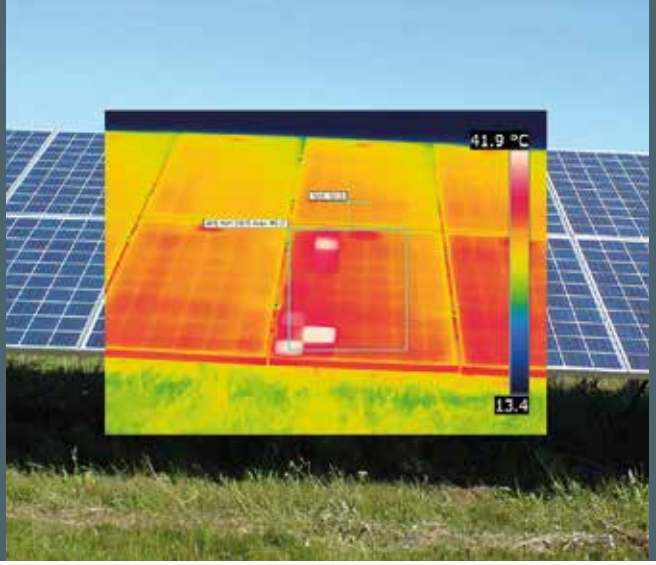
With the four phases of the Fraunhofer ISE quality cycle – yield prediction, random sample measurements of modules, system testing and performance check – we ensure comprehensive quality control of PV modules and power plants. Together with good planning and the usage of high-quality components, this is decisive for efficient operation and high yield of a PV system, and can thus increase 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 1.8% 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. Beyond this, our customised 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 optimisation and system design.

FURTHER INFORMATION

Staff	127
Staff: Full-time equivalent	91
Journal articles and contributions to books	12
Lectures and conference papers	27

www.ise.fraunhofer.de/en/publications/30



Thermographic investigation of a solar generator in a photovoltaic power plant. The high-resolution infrared image of a faulty module is superimposed over the digital photo and reveals individual solar cells with noticeably higher operating temperatures. The result is a clear indicator for yield losses and future risks affecting the reliability of the affected module.

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CONDUCTIVE ADHESIVES – FLEXIBLE, RELIABLE AND LEAD-FREE

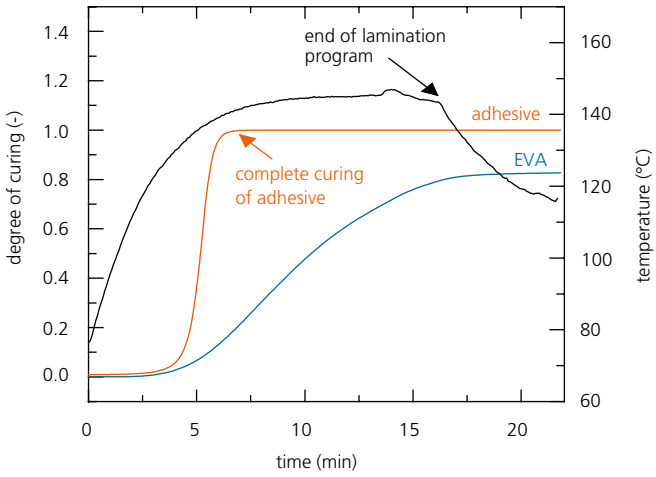
How can those solar cells which cannot be soldered be connected within a module? With an electrically conductive adhesive. The advanced technology is already used successfully to connect back-contact cells, heterojunction cells and solar cells without busbars, and offers advantages compared to soldering. Adhesive joints create less thermo-mechanical stress. They function on many novel metallization designs and thus enable new, highly efficient contact structures at the cell level. In addition, the adhesives are lead-free and the application process is gentle. The task of our expertise team is to investigate the materials with regard to their processing properties and long-term stability, and to develop module concepts based on adhesion technology, so that high-efficiency cells can be connected durably and without losses.

Ulrich Eitner, **Torsten Geipel**, Harry Wirth

There is a great need for research on the electrical and mechanical material properties of conductive adhesives. In particular, our work is concentrating on reducing material costs, clarifying degradation mechanisms and evaluating new processing steps for module production.

The curing of the adhesive affects the mechanical and electrical properties of the joint. We have developed a model to determine the curing kinetics, which can calculate the degree of curing for any arbitrary temperature profile. The autocatalytic reaction model was parameterised by dynamic differential scanning calorimetry. The procedure can be transferred to the cross-linking reaction of ethylene vinyl acetate (EVA), so that simultaneous curing of the adhesive and EVA in the lamination process can be simulated.

1 *One application of conductive adhesives is to directly contact the grid fingers of a solar cell without front busbars. This concept allows material to be saved, while still applying standard technology.*



2 *Simulated curing of a conductive adhesive and EVA.*

A practical application is e.g. calculation of the curing of the adhesive and EVA during lamination of a module consisting of metal wrap-through solar cells. Fig. 2 presents the calculated curing of both materials during a given lamination program. It can be seen that the adhesive is cured significantly earlier than the EVA. Thus, the adhesive already has its high final strength while the EVA is still soft. Due to the high mechanical pressure during lamination, this kinetic behaviour can lead to local mechanical loads and cell breakage.

Conductive adhesives represent a reliable connection technology with great potential for connecting high-efficiency solar cells.

DIRECT CONTACTING OF ALUMINIUM BY ULTRASONIC SOLDERING

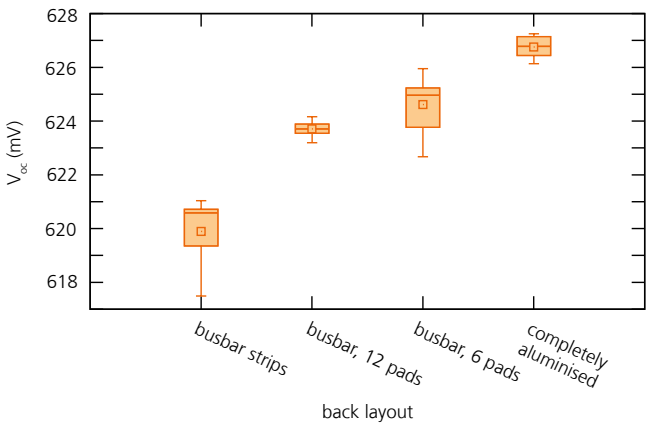
As part of our research and development work, we have succeeded in contacting the aluminium back surface of crystalline silicon solar cells by ultrasonic soldering. Due to this new contacting technology, solar cells no longer need a silver back contact for connection. Instead of the previously used silver, tin contacts (Fig. 1) are applied to the aluminium layer which covers the whole back surface. This reduces the production costs in comparison to alternative processes with silver pastes significantly, by about 3 euro cents per cell at present. In addition, the cell efficiency can be increased by 0.2% by dispensing with the silver back contact (Fig. 2).

Dirk Eberlein, Ulrich Eitner, Peter Schmitt, **Marco Tranitz**, Harry Wirth

1 *Detail of tin contacts on the aluminised back surface of a crystalline silicon solar cell.*

In the current state of the art, the back surface of a conventional silicon solar cell is almost completely covered by an aluminium coating. This coating cannot be contacted with conventionally used solders, fluxes, processing profiles or soldering equipment. The reason is the very stable oxide layer which surrounds the aluminium particles. In order to contact conventional silicon solar cells with cell connectors, silver contacts are deposited onto the back of the cell, which are subsequently soldered to a solder-coated cell connector.

With a new contact technology, ultrasonic soldering, we have attached tin contacts onto the aluminised back surface of the solar cell which are mechanically stable, durable and electrically conductive. These can then be soldered to standard cell connectors. The new technology means that expensive silver contacts are no longer required. For the research project, cell strings and modules were produced in formats from 1-cell through 16 cells to 60 cells. These have passed important durability tests from the IEC 61215 standard, in particular temperature cycling, damp heat and mechanical load tests. Costs were reduced significantly with the new connector technology and further increases in efficiency are still possible.



2 *Comparison of back busbar layouts: V_{oc} gain by layout adaptation.*

The contact durability was investigated in the accredited TestLab PV Modules of Fraunhofer ISE. The project was supported by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) within the "Kalus" project (contacting of aluminium coatings on solar cells), in cooperation with the company Gebr. Schmid GmbH.

1

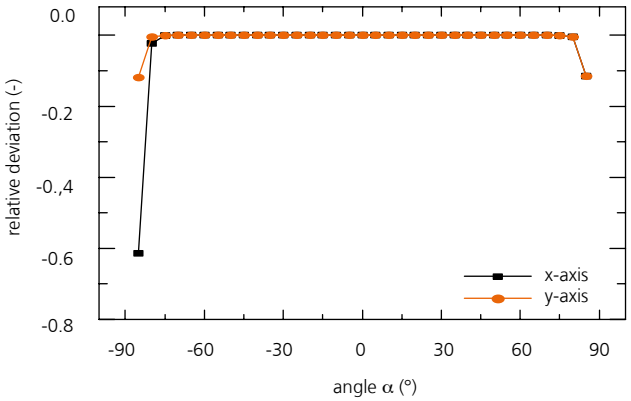
LARGE-AREA REFERENCE CELL LARC®

Reference cells are favoured for the calibration of solar cells, solar modules and solar simulators. Conventional reference cells corresponding to the current state of the art usually consist of small solar cells with special materials. These two restrictions cause appreciable disadvantages, such as limited measurement accuracy and susceptibility to errors. The concept of the Large-Area Reference Cell (LARC®) allows application of the same cell technology with similar materials to the test object and a large active cell area. Due to these advantages, it is no longer necessary to post-process the measurement data, a common source of error, and the accuracy of the measurements can be improved.

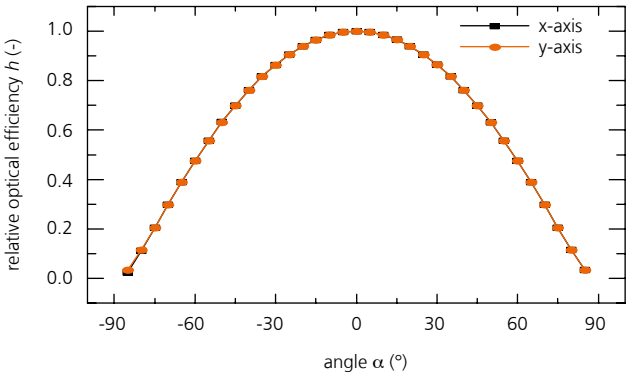
Stefan Brachmann, Thomas Schmidt, **Peter Schmitt**, Marco Tranitz, Harry Wirth

Our large-area reference cell is based on modified module technology for crystalline silicon modules and components (solar cell, encapsulation, etc.) as specified by the client. This reduces the need for error-prone corrections. Further, the use of a large-area solar cell reduces the effect of inhomogeneity in the radiation from solar simulators. The reference cell is equipped with an accurate, internal temperature sensor. Special contact insulation allows electrical insulation without the loss of thermal contact. The reference cell is mounted in a casing we developed to protect it against environmental influences. This casing includes a contact interface with robust sockets to attach the measurement cables. The black, anodised surface and the geometrical configuration reduce reflections and shading of the solar cell.

1 *LARC® construction with a commercially available crystalline solar cell of dimensions 156 mm x 156 mm, cover glass, frame and connection box.*



2 *The relative deviation of a LARC® with a frame compared to one without a frame shows the shading of the cell by the frame for different angles of rotation around the x and y axes.*



3 *Ray-tracing results for the relative optical efficiency value including the cosine losses versus the angle of rotation around the x and y axes. No visible effects of reflection due to the frame are visible.*

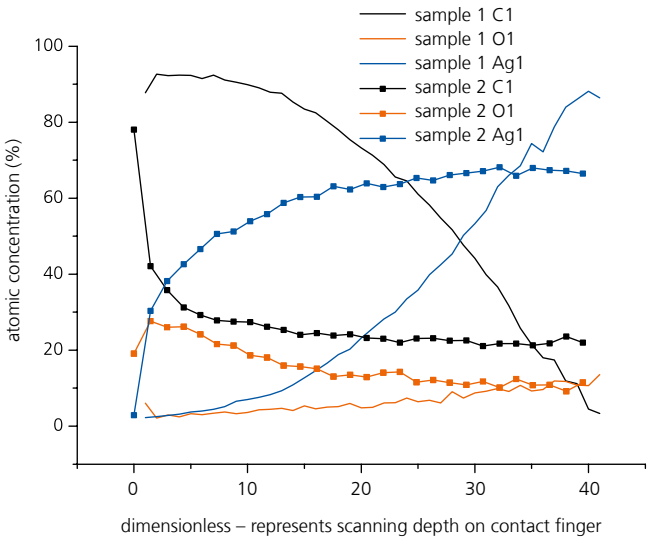
"SNAIL TRAILS" AND DEGRADATION ANALYSIS OF PV MODULES

Material faults, production errors or inappropriate handling are only some of the causes leading to changes in the optical and electrical properties of PV modules. These often provoke questions about their origins, long-term effects or the scope of manufacturer guarantees. So-called "snail trails" (Fig. 1) are an example of the effects which we investigate, aiming to identify the process mechanisms und thus contribute to avoiding such damage.

Ines Dürr, Stephan Hoffman, **Cornelia Peike, Daniel Philipp**, Harry Wirth

1 *Strongly discoloured contact fingers and busbar after accelerated aging.*

2 *At the marked position, cell damage was artificially induced by a mechanical load. A new "snail trail" formed there after accelerated aging.*



3 *Concentration depth profiles from the Auger spectroscopic investigations on extracted contact fingers. For sample 1, the oxygen concentration increases with the silver concentration, which is interpreted as an indication of silver oxide formation. The second sample does not confirm this hypothesis. An elevated oxygen signal is also evident here, which decreases together with the carbon signal from the encapsulation material.*

"Snail trails" is a term referring to linear discolorations on the cells of PV modules. On closer examination, it becomes evident that it is the contact fingers which have become darker. The investigation of affected modules with electro-luminescence analysis showed a correlation between the occurrence of discoloration and cell breakage. The trails often differ in intensity from one module to the next. Modules with snail trails often also show discoloration in the edge region of the cells. Raman spectroscopy confirmed a connection between cell fractures and discoloration of the contact fingers. Analysis provided proof of a reaction process in the encapsulation polymer resulting from oxygen diffusion.

Samples of discoloured contact fingers were extracted from two modules and subjected to analysis by Auger spectroscopy (AES). In one case, indications were found for oxide formation on the surface of the contact fingers. Measurement of the second module also revealed a higher oxygen concentration; however, it was not on the surface of the contact finger but in the remnants of the encapsulation polymer (EVA) (Fig. 3). Parallel to the analytical investigations, accelerated aging tests were made, whereby additional cell fractures had been generated before the tests (Fig. 2). Again, the responses were not uniform. In the damp heat test, the discoloration disappeared from some modules but not from others. UV exposure tests of affected and new modules caused discoloration in some cases.

UV STABILITY OF POLYMER MATERIALS IN PV MODULES

In operation, PV modules are exposed to different degradation factors. For polymer materials, the damaging effect of UV radiation is particularly relevant. Investigating the UV stability of polymer materials in PV modules is therefore an important task within the joint research project on "Reliability of PV Modules II". Fraunhofer ISE, which also coordinates the project, is working on the UV stability of the materials and non-destructive investigation methods with the goal of predicting the service life of PV modules. The results show clearly that interaction between the materials used and the module configuration affects the material degradation.

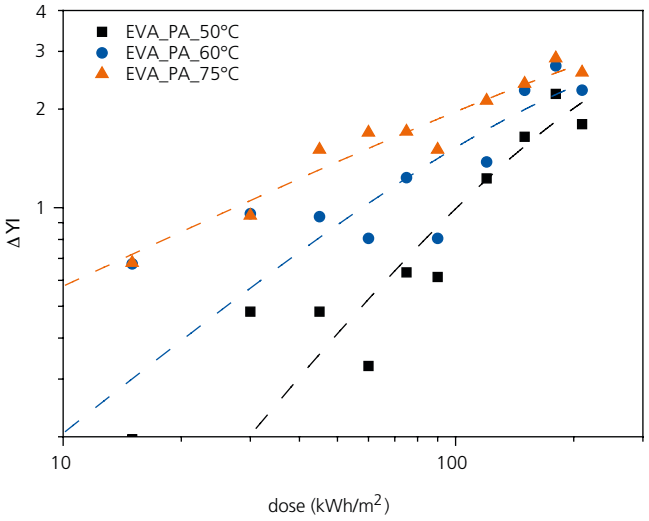
Konstantin Apin, Myriam Hummel, Michael Köhl, **Cornelia Peike**, Karl-Anders Weiß, Harry Wirth

To investigate the UV-induced aging of polymer materials in PV modules and the effect of temperature on the ongoing aging processes, series of experiments were conducted in which the spectrum of the UV radiation was varied and different sample temperatures were maintained. The test samples are constructed analogously to industrially manufactured PV modules (Fig. 1) and consist of solar glass, various encapsulation materials (polyolefins and EVA) and back covers with different permeability to moisture (polyamide and glass).

The transmittance of the materials remains unchanged up to a UV dose of 150 kWh/m², which corresponds to approximately two years' exposure in Central Europe. Up to 180 kWh/m², the transmittance decreased slightly. This decrease was similar for all testing temperatures for laminates with an impermeable back cover (glass – glass). In the laminates with a permeable back sheet, non-destructive Raman spectroscopic measurements (Fig. 2) showed a clear effect of the temperature on the resulting fluorescence, which is an indicator for polymer aging.

1 *In addition to yellowing, crystal-shaped delamination can also occur in PV laminates.*

2 *Raman spectroscopic investigation of the encapsulation polymer through the front glass cover of a test sample.*



3 *Change in yellowness index (YI) of EVA encapsulation materials in combination with polyamide back sheets as a function of UV dose and temperature.*

In addition, it was observed that the yellowing of the glass-glass laminates is more pronounced than for the laminates with a polyamide back sheet, which suggests a significant influence of the permeation properties of the backing materials on the aging of the encapsulation.

The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB) and the companies Solar Fabrik AG, Solarwatt GmbH, Bosch Solar Energy AG and Solon Energy GmbH.

ACCURATE POWER AND PERFORMANCE EVALUATION OF PV POWER PLANTS

Determining the Performance Ratio (PR) of a PV power plant is a frequently demanded task in practice, be it at the time of commissioning, the end of guarantee periods or before a sale. Fraunhofer ISE has developed a procedure – and tested it successfully in real, large-scale projects – with which the annual value of the Performance Ratio can be determined with great accuracy within a few weeks. At the same time, the data from the power plant's own monitoring system is validated by temporary application of calibrated and accurate measurement technology. In this way, already existing and future operation data can be used for independent performance evaluation by Fraunhofer ISE.

Klaus Kiefer, Björn Müller, Christian Reise, **Andreas Steinhüser**, Harry Wirth

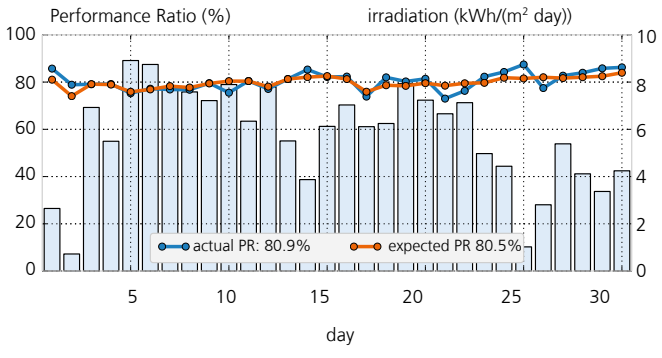
1 *Calibrated radiation sensors to validate the installed measurement technology.*

2 *Mobile, highly accurate measurement equipment.*

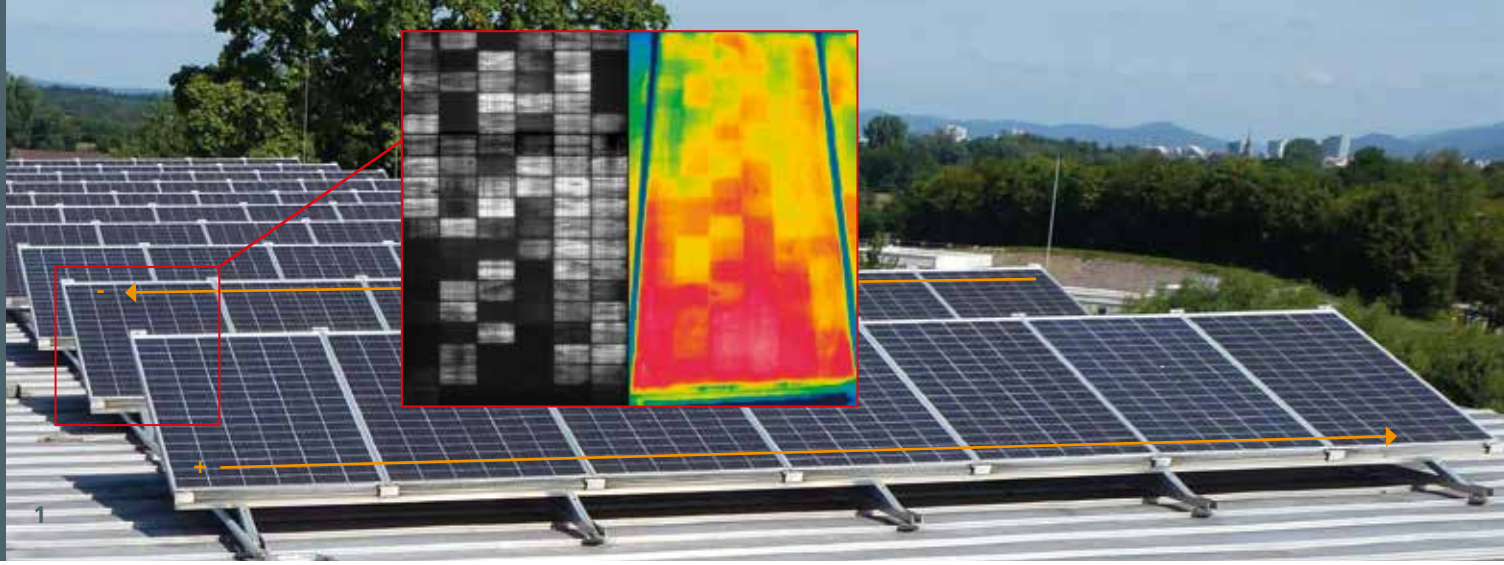
The data from the operator's own operation monitoring system are analysed, validated and, if necessary, corrected by the use of highly accurate measurement technology (Figs. 1 and 2). These subsequently serve to determine the current Performance Ratio (actual PR) of the power plant. The recorded meteorological data are then fed into the model which had already been prepared for yield prediction or is newly created specifically for the power plant. In this way, the expected value of the Performance Ratio (expected PR) can be determined and compared to the actual value.

In order to achieve high accuracy, the system configuration and shading of the solar generator are checked on site and possible deviations from the planning data recorded. To determine the system yield, we use the highly accurate values from the calibrated meter of the grid operator and the radiation values which we have validated. The temperature coefficients and the low-light response of the modules are determined by accurate measurements in our measurement laboratory.

The newly developed procedure offers further options for analysis and application. For example, yield data over a longer period can be evaluated also retrospectively, the analysis of the first month of operation can be projected statistically to represent a typical year of operation or yield losses due to output limits imposed by the grid can be quantified.



3 *Graph comparing the expected and actual PR for a multi-mega-watt PV power plant.*



1

PID – THEORY AND PRACTICE

Potential-induced degradation (PID) can be understood as a designation for aging effects which arise due to the potential difference between cells and earth. In the past, a form of PID which can lead to a decrease in power has been observed for crystalline PV modules, without the module having externally visible damage. In everyday speech, this effect is often also called PID. At Fraunhofer ISE, the causes and driving factors for the occurrence of this effect are being investigated, together with its influence on the yield of PV generators.

Sönke Dohse, Stephan Hoffmann, Klaus Kiefer, Daniel Philipp, Andreas Steinhüser, **Carola Völker**, Harry Wirth

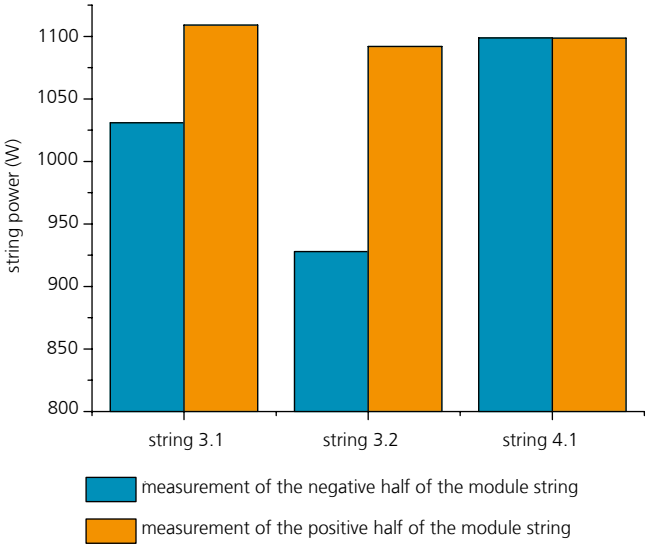
Due to the voltage between cells and earth (frame / front glass cover), positive ions can migrate into the solar cell, for example, reducing the output power. At present, we are investigating different generation mechanisms and models for this phenomenon.

Since 2011, we have measured the influence of environmental factors such as climate and soiling on the PID effect at outdoor test sites on Gran Canaria and in Freiburg. In addition to investigations at the cell and module level, the system level has also been studied since last year. The aim is to determine the actual effect of PID on the yield of power plants in which PID-sensitive modules are installed.

The extent of the PID effect is determined by power measurements and thermography on site, taking specific factors for the location and the climate into account. Further tests are made in the laboratory on modules that show pronounced degradation.

Fig. 2 shows the power values for measured half-strings of an investigated PV plant. It is evident that the half-strings toward

1 *Generator with affected modules near Freiburg.*



2 *Measured power values for half-strings from a plant affected by PID.*

the negative pole of 3.1 and 3.2 generate significantly less power. The PID sensitivity of the modules was confirmed in the laboratory. String 4.1 does not show this behaviour.

We are also investigating the reversibility of the PID effect. For example, a PID test based on the current draft standard IEC 62804 was carried out on modules after they had completely recovered from PID-induced effects. By comparison of the real and artificially induced damage, the results of the PID test in the laboratory can be qualitatively classified.

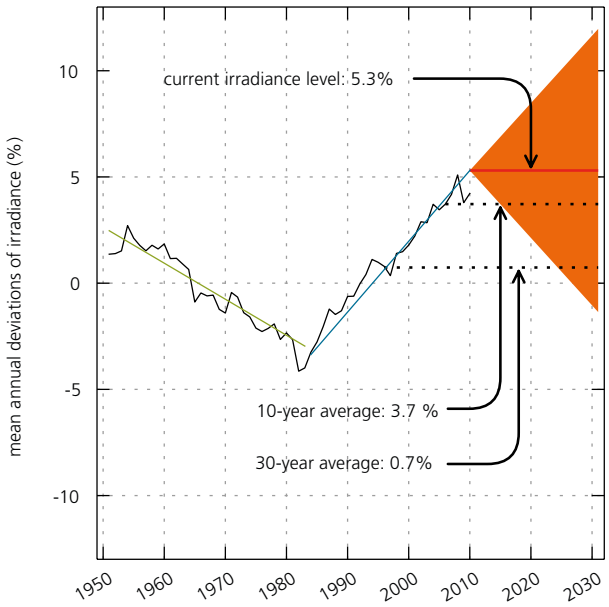
PV POWER PLANTS GENERATE MORE ELECTRICITY THAN EXPECTED

The most important input for yield prediction is the solar irradiance at the respective site. However, the global radiation incident on the earth's surface is subject to long-term changes, a phenomenon which is known as "global dimming and brightening". In Germany and large areas of Europe, an increase in solar radiation (brightening) has been observed since the beginning of the 1980's. As the averages for solar radiation over a period of 30 years have been used for yield predictions up to now, the real yields are significantly higher than the predicted values. Current time series from satellite data can be used to take account of this trend in yield predictions.

Anton Driesse, Laura Hardt, Klaus Kiefer, **Björn Müller**, Christian Reise, Harry Wirth

1 *Photovoltaic power plant.*

In cooperation with scientists from ETH Zürich and the German Meteorological Service (DWD), Fraunhofer ISE has investigated long-term changes in global radiation in Germany. Terrestrial measurement data from different stations of the DWD were evaluated. The investigation confirms long-term trends in global radiation measured at the ground (global dimming and brightening) and allows the conclusion to be drawn that the current radiation level in Germany is about 5% above the long-term average (Fig. 1). The main causes of these fluctuations are considered to be changes in the aerosol content of the atmosphere and changes in cloud cover. Up to now, yield predictions for PV power plants have used averages for the solar radiation taken over the longest possible periods in the past to predict the radiation expected in the future. In Germany, usually 30-year averages from the DWD are used. However, the current solar radiation level is not taken sufficiently into account by this practice. On the basis of long-term global radiation and power measurements in commercially operated systems that are monitored by Fraunhofer ISE, it was demonstrated that usage of the 30-year averages for yield predictions leads to underestimation of the yields by 4–5%. As it is currently not possible to predict future developments in solar radiation, and the present global radiation level is evidently above average, Fraunhofer ISE uses satellite data for the last complete 10 years for its yield predictions.



2 *Annual deviations of the global irradiance from the average for 1951 to 2010 in Germany (moving average: black line). Linear trend of the dimming and brightening phases: green and blue lines respectively. The 30-year average underestimates the present irradiance level. The 10-year average is only slightly lower than the current irradiance level.*

OPERATING PERFORMANCE OF COMPLEX BIPV SYSTEMS WITH a-Si/µ-Si MODULES

Within the "Solarvalley-BIPV" research project that was coordinated by Fraunhofer ISE, both novel BIPV components and also methods for detailed yield analyses were developed for building integrated photovoltaic systems (BIPV). In addition, high-quality measurement data sets were acquired for two grid-connected systems with a-Si/µ-Si modules. Comparison of the simulated results with measured data provides insights for BIPV component development and yield optimisation under typical BIPV conditions, such as higher module temperatures and differently oriented subsystems.

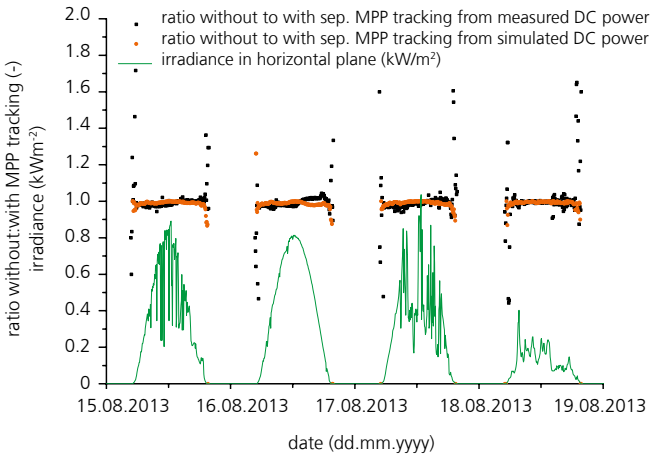
Anselm Kröger-Vodde, Tilmann Kuhn, Nicole Römer, Wendelin Sprenger, **Helen Rose Wilson**, Hans-Martin Henning

For the first time, the concept developed by Fraunhofer ISE for angle-selective PV glazing, PVShade®, was implemented in a BIPV pilot plant. Ten PVShade® triple glazing units with a total area of about 15 m² were installed in the new building of Fraunhofer ISE in Freiburg. The angular selectivity is achieved by laminating two thin-film modules, which each feature an identical striped pattern, to each other with the stripes juxtaposed. The angle-selective configuration allows outward viewing and simultaneously provides solar control that varies with the season and time of day (Fig. 1).

For the yield simulation, the geometrically complex module configuration and shading by a neighbouring building wing were taken into account by ray-tracing calculations. The effect of high module temperatures and the interaction between the modules and the inverter were also modelled. The agreement between measured data from the scientific monitoring programme and simulated values for the DC current was very good, with an average difference of less than 3%.

1 *Angle-selective PVShade® triple glazing units in the spandrel zone.*

2 *Differently oriented, vertical a-Si/µ-Si modules at MasdarPV in Ichtershausen.*



3 *Ratio of the DC power from the system in Ichtershausen for parallel-connected, east/west oriented, vertical module strings without:with separate MPP tracking; black – from measured DC power values, red – from simulated values, green – irradiance in the horizontal plane.*

The effect of connecting differently oriented module areas was investigated for a further a-Si/µ-Si system (Fig. 2). Both the measurements and the yield simulations for the year up to September 2013 resulted in an electric mismatch factor below 1% (Fig. 3). On this basis, the additional complexity of separate MPP tracking for each orientation is hardly justified for this type of system.

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

SOLAR THERMAL TECHNOLOGY

When energy systems are transformed to include a larger proportion of renewable energy, solar thermal energy plays a major role. How this role is played in different economic systems and climatic zones depends on cost developments in production and distribution. Research and development can make their contribution by developing more cost-effective materials, manufacturing processes and total systems which are optimised with regard to investments and yield.

Our activities in the business area of Solar Thermal Technology encompass the entire market from low-temperature to high-temperature applications: solar thermal, flat-plate and evacuated tubular collectors have multi-facetted applications ranging from domestic hot water and solar-assisted space heating systems to cooling and refrigeration. In the context of competition with photovoltaics for installation areas, new developments concerning façade-integrated collectors or collectors combined with photovoltaic electricity generators are important. Operating temperatures ranging from 150 °C to 550 °C can be reached with linearly concentrating collectors. They are used not only in large, solar thermal power stations, but also in less expensive variants to generate process 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.

In 2013, we have combined our activities on decentralised water purification by thermal membrane distillation, ultrafiltration and reverse osmosis. With the help of collectors and photovoltaics, we can also construct completely autonomous systems which are optimised for the prevailing water quality. In future, we also plan to apply our expertise to the separation of industrial materials systems.

In countries with a high proportion of direct solar radiation, solar thermal power stations offer enormous potential to generate electricity flexibly and inexpensively, both for daily peak loads and for longer periods with higher loads. This can be achieved either by hybridisation (combination with fuel-fed heat generators) or heat storage, on which we are working intensely.

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

Special facilities 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 the Solar Keymark

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www.ise.fraunhofer.de/en/publications/35

Scheffler reflector to generate steam to drive a 1 MW turbine using waste heat in Rajasthan, India.

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THERMALLY ACTIVATED BUILDING SYSTEMS OF ULTRA-HIGH PERFORMANCE CONCRETE

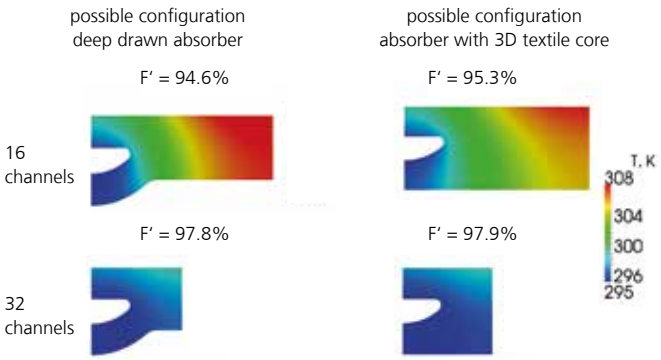
Within the "TABSOLAR" research project, Fraunhofer ISE is developing novel building components with integrated fluid channels on the basis of ultra-high performance concrete (UHPC). Multi-functional components such as building-integrated solar collectors or thermally activated building systems (TABS) for new buildings and building renovation are to be implemented with innovative production methods. We have already successfully deposited a spectrally selective coating onto the first UHPC samples. Further, our thermal simulations have demonstrated that high thermal efficiency can be expected with UHPC if components are suitably dimensioned.

Paolo Di Lauro, **Michael Hermann**, Carmen Jerg, Doreen Kalz, Angelina Katsifaraki, Franziska Kennemann, Lotta Koch, Eric Laurenz, Christoph Maurer, Lena Schnabel, Dominik Wystrcil, Werner Platzer

In the "TABSOLAR" joint research project, we are cooperating with five project partners to develop multi-functional, low-temperature building components such as walls, ceilings or floors, which fulfil structural (e.g. load-bearing wall), thermally activated (fluid-conducting), thermally passive (thermal insulation) and design (structure, colour, coating) functions. The basis for the novel concept is ultra-high performance concrete (UHPC), which can be formed into very finely structured, material-saving and yet also extremely strong building components.

Two possible new production technologies are being investigated in parallel as part of the project: a vacuum deep-drawing process which we have developed and patented, and casting around a core of knitted, three-dimensional channels. The channel structures are designed with the help of our FracTherm® procedure. We have successfully deposited

1 *UHPC plate with a spectrally selective coating, which was deposited in our sputter coater. The absorptance α of the coating, which has not yet been optimised, is around 94%, the emissivity $\varepsilon_{100\,°C}$ is around 10%, which is already very good.*

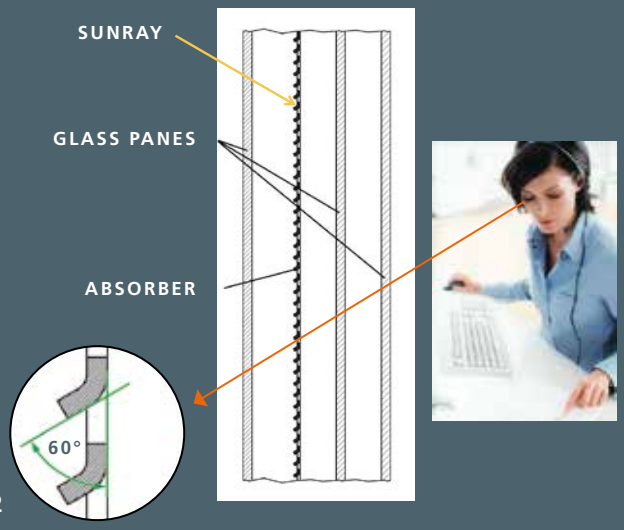


2 *Temperature distribution and collector efficiency factor F' for different examples of channel configurations (stationary). The number of channels refers to an absorber width of 1 m. The interior channel height is 4 mm.*

spectrally selective coatings onto the first UHPC samples (Fig. 1). In comparison to metals, the thermal conductivity of UHPC is low; we have measured it to be 1.9 W/(mK) at 20 °C and 1.6 W/(mK) at 100 °C. We have thus prepared thermal models and carried out numerical simulations to determine the collector efficiency factor F', which is a measure for the thermal efficiency of a solar absorber (Fig. 2). The determined values are in the same range as for typical, state-of-the-art metal solar absorbers or better.

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

www.tabsolar.de



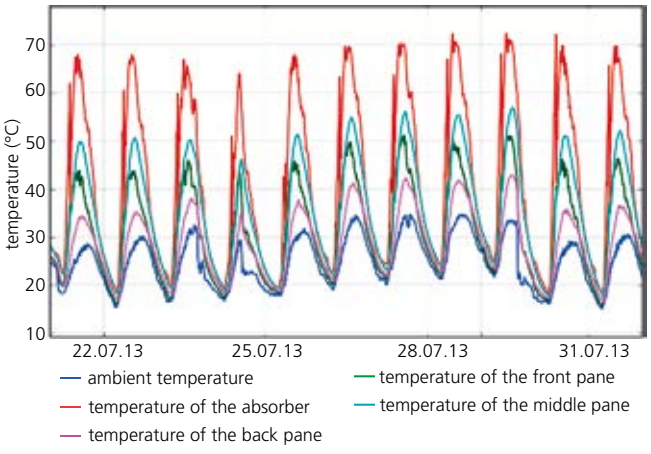
HEATING AND COOLING WITH TRANSPARENT FAÇADE COLLECTORS

In the European "Cost-Effective" research project, new building-integrated solar systems were developed and installed in pilot buildings. After the project had ended, the measurement results for a collector field with semi-transparent, solar thermal façade collectors were analysed further. They demonstrated that the transparent collectors can contribute both to heating – via thermally activated building systems (TABS) – and to cooling – via an adsorption chiller. The most important insight, however, is that the heat flux between the collector and the indoor space is similarly low to that for conventional solar-control glazing.

Paolo Di Lauro, Damien Gasnier, Michael Hermann, Tilmann Kuhn, **Christoph Maurer**, Thibault Pflug, Hans-Martin Henning

Fig. 1 shows the semi-transparent collectors, which form the façade of a stairwell. As shown in Fig. 2, the collectors consist of three glass panes and an absorber, which has fins and slot-shaped openings. Whereas the fins can absorb the solar radiation particularly well due to their tilt angle, the slots provide visual contact between indoors and outdoors. The additional costs in comparison to a conventional façade with three glass panes amount to only 10–15%. In winter, rays from the lower-standing sun penetrate the slots better and contribute to the building heating, whereas little direct sunlight enters the building in summer, resulting in minimal overheating. In comparison to an opaque wall, a transparent collector can lower the annual energy consumption and enables outward visual contact.

1 *Semi-transparent, solar thermal façade collectors; pilot installation in Slovenia.*
2 *Schematic drawing of a semi-transparent collector with three glass panes and a semi-transparent absorber with fins and slot-shaped openings.*



3 *Change in temperature with time for the different collector layers.*

Fig. 3 presents the temperatures of the different collector layers during the hottest days of the measurement period. The temperature of the indoor pane is about 10 °C higher than the air temperature in the stairwell, which is connected via vents to the outdoor air. A comparable temperature difference between the indoor pane and the indoor air temperature also occurs for conventional solar-control glazing. Thus, the heat emitted by these semi-transparent collectors into the indoor space is similarly low to that for conventional solar-control glazing.

The work was supported by the European Union (EU) within the "Cost-Effective" project.

www.cost-effective-renewables.eu

1

MODEL-BASED ANALYSIS OF MEASUREMENT DATA FROM "SOLAR-ACTIVE-HOUSES"

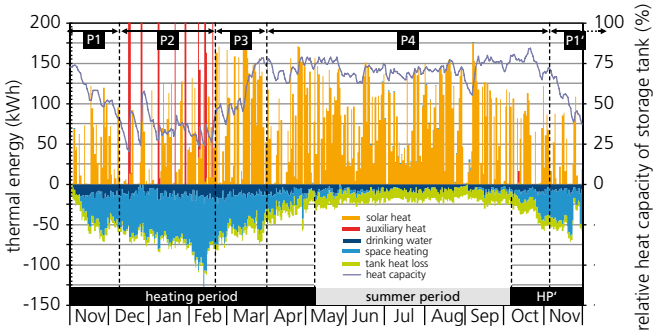
The European Union (EU) specifies nearly zero-energy buildings as the standard for new buildings from 2020 onward in its Energy Performance of Buildings Directive from 2010. As an alternative to a very pronounced reduction in the building heat demand, fossils fuels with an extremely unfavourable primary energy contribution can be replaced by an increased proportion of renewable energy. Solar-Active-Houses are nearly-zero energy buildings in which more than 50% of the heat required for space heating and domestic hot water is generated on the building surface. In the "HeizSolar" project, nine Solar-Active-Houses representing the current market are being comprehensively monitored and their optimisation potential determined by simulation.

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

Solar-Active-Houses feature good thermal insulation, a large collector area and a large thermal storage tank. The concept is based on solar heat generation during the heating period. Operation of the storage tank can be divided into four phases (Fig. 2). In the discharging phase P1 at the beginning of the heating period, heat is supplied by the currently generated and stored solar heat. In the supplementary heating phase P2 in the middle of winter, auxiliary heating is needed. In the charging phase P3, the prevailing solar radiation is sufficient to provide the required heat and to charge the storage tank. In phase P4, the storage tank is completely charged.

In a free-standing house, typical solar thermal fractions of about 60% can be achieved with relatively small water tanks with a volume of several cubic metres, which represent storage for about one week with respect to the heating demand in the middle of winter. By contrast, large solar thermal fractions exceeding 90% demand seasonal storage

1 *Solar-Active-House with a solar thermal fraction of 100% in Kappelrodeck, Germany.*



2 *Characteristic operating phases of a Solar-Active-House with a solar-thermal fraction of about 70%. The graph shows the thermal gains and consumption (left-hand axis) and the thermal capacity of the storage tank (right-hand axis).*

of the solar heat generated in summer until the middle of winter and a tank volume which is ten times larger. The simulation-based optimisation concentrates on a yield-optimised and cost-optimised relationship between building efficiency, collector area and tank volume, on identifying efficient system hydraulics and on increasing efficiency by optimised operation management.

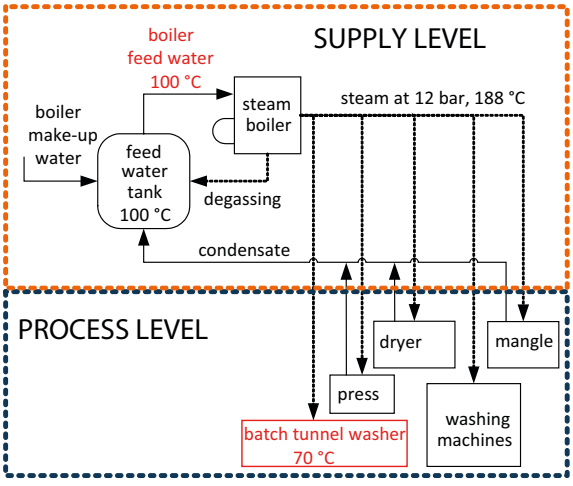
The "HeizSolar" project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB).

www.DieSolarHeizung.info

INTEGRATION OF SOLAR PROCESS HEAT INTO COMMERCIAL LAUNDRIES

Solar thermal systems can meet a significant fraction of the heat demand in many industrial and commercial processes. In the "SoProW" project, Fraunhofer ISE is coordinating a consortium of partners from the solar thermal industry, the laundry sector, research institutes and software developers. The goal is to develop a concept for the laundry branch for optimised and standardised solar thermal heating support. For dynamic system simulations, we used the "ColSim" program that was developed at Fraunhofer ISE. We applied it to determine the possible solar gains for integration of solar process heat into different processes. In addition, we investigated how future changes in the heat demand would affect solar gains.

Annabell Helmke, Stefan Hess, Anton Neuhäuser, Werner Platzer



2 *Laundry with its steam network and processes. The steam generated by the boiler is supplied directly to the applications or via heat exchangers. The integration processes for solar process heat, which were investigated as examples, are marked in red.*

1 *Batch tunnel washer with several chambers at different temperature levels.*

Laundries offer many possible options for integrating solar heat. We analysed their suitability with regard to the temperature and pressure levels, the heat transfer medium and the heat demand. In addition, we investigated the effect of modified load profiles for the examples of solar pre-heating of boiler feed water (supply level) and solar heating of the batch tunnel washer (process level). The following scenarios leading to the same reduction in the daily heat demand were investigated:

A) Reduction in the amount of textiles washed: the operating time for the whole process chain becomes shorter; the thermal power demand remains unchanged.
B) Heat recovery in the batch tunnel washer: Reduction of the thermal power demand for this process step, operating time remains unchanged.

With the original heat demand, the solar thermal system consisting of evacuated tube collectors and a buffer tank achieved a higher yield due to the lower integration temperature into the washing sequence. For variation according to scenario A), higher yields are achieved for the boiler feed-water integration when the load reduction exceeds 33%. For scenario B), this occurs only after a load reduction of 50%. This demonstrates that to evaluate the future reliability of predicted solar yields, not only the possible absolute change in heat demand but also the way the load profile changes can be decisive. The inclusion of such aspects into system simulations can increase the investment security appreciably, e.g. for contractors.

Our work is also input into IEA Task 49, "Solar Heat Integration in Industrial Processes"

http://task49.iea-shc.org

1 A

1 B

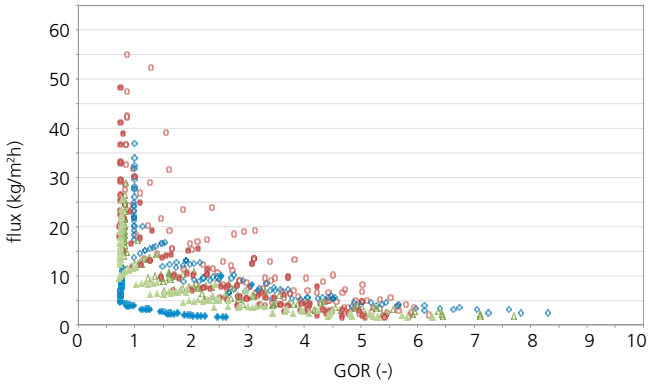
DEVELOPMENT OF MEMBRANE DISTILLATION MODULES AND SYSTEMS

Purification of seawater and brackish water is an essential component of the drinking water supply in many countries. The development of smaller, decentralised systems for this application is becoming increasingly important, as is also the energy-efficient and sustainable treatment of industrial waste water and the recovery of materials. Innovative treatment processes that suit the specific individual requirements are needed. Extensive work on membrane distillation (MD) is carried out at Fraunhofer ISE. A newly developed simulation model, which has been validated by numerous measurements, allows coupled heat and mass transport to be studied from the membrane, through the module, to the systems level.

David Düver, Florian Groß, **Joachim Koschikowski**, Christiane Pohlisch, Martin Rolletschek, Rebecca Schwantes, Daniel Winter, Werner Platzer

Membrane distillation (MD) is a thermal separation process, in which a hydrophobic, microporous membrane is used for separation of the liquid and vapour phases. The liquid sol is held back by the membrane. A temperature difference between the two fluids at the membrane interfaces serves as the driving force for the separation. The process can be used both for seawater desalination and also to purify different types of waste water or process fluids.

1 A/B *Pilot plant on Gran Canaria for solar thermal desalination of seawater based on membrane distillation.*



2 *Simulation results for widely varying MD module configurations, which indicate the opposing directions for optimising energy efficiency – characterized by the degree of heat recovery (GOR) – and area-specific productivity – characterized by the flux. The simulation allows the application-specific optimum to be determined.*

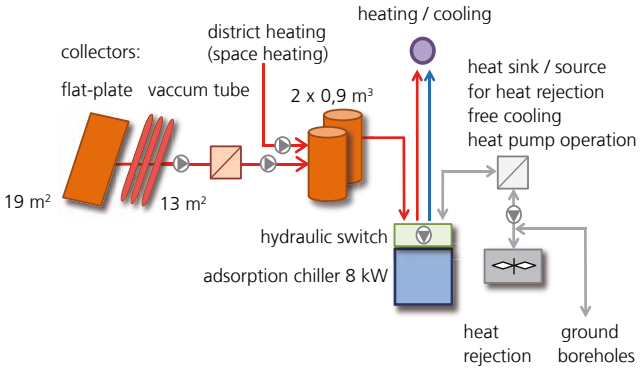
The ideal module and membrane specifications can vary widely, depending on the application and goal. We cooperate with industrial partners to develop modules, systems and module components. In addition to experimental work in the laboratory and pilot systems in the field, a newly developed, very detailed physical simulation model is applied to carry out sensitivity analyses, parameter studies or corresponding module and system dimensioning. For example, the effect of changes in the membrane parameters on the entire process was studied for different concentrations of seawater, so that the membrane could be specifically optimised. As shown in Fig. 2, simulations were used for module optimisation, e.g. to determine which module configuration with which geometrical properties is the most energy-efficient or highest-yield variant for desalinating seawater with 35 g salt per litre water at a driving temperature of 80 °C.

1

SYSTEM DEVELOPMENT AND OPERATION ANALYSIS FOR SOLAR COOLING

The application of solar energy to cooling and air-conditioning has been advanced by Fraunhofer ISE for almost 20 years. The activities encompass R&D projects at the materials and components level, system modelling and simulation to support planning and test concepts, and monitoring and operation analysis. One main objective of the SolCoolSys project led by Fraunhofer ISE is to test a standardised system development for solar cooling in the low power range in field tests. The aims are to reduce the risk of error during installation and operation and to extend usage of the adsorption chiller and cooler by adding heat pump operation and free cooling.

Florian Mehling, Peter Schossig, **Edo Wiemken**, Hans-Martin Henning



2 *Schematic diagram of the solar cooling system at the Technical College. The system is equipped with two different collector arrays for educational purposes. An additional connection to the district heating network ensures that the rooms are heated in winter. The cooling and heating power is distributed via two ceiling-mounted ventilation coolers and a floor heating loop.*

1 *Installed system for solar cooling and solar-assisted heating at the Richard Fehrenbach Technical College in Freiburg, Germany. On the right is an adsorption chiller with a rated cooling power of 8 kW.*

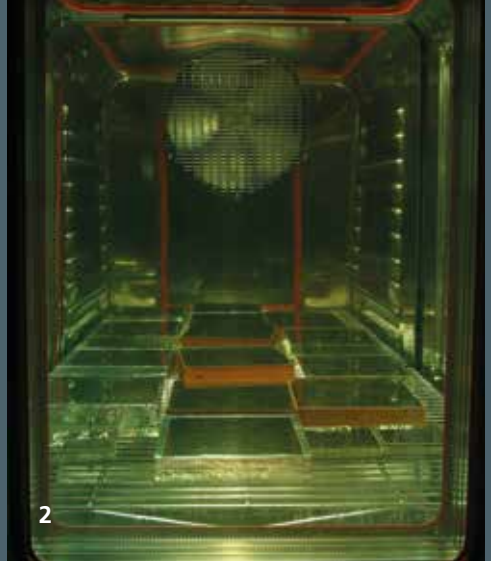
Adsorption chillers from Sortech AG and flat-plate collectors from Solvis GmbH have been installed within the SolCoolSys project. Both manufacturers are also project partners. Six systems were installed with rated cooling power at the consumer level of between 8 and 15 kW. Switching between the operation modes of solar cooling, natural cooling via the cooler and heat pump operation is achieved with a specially developed group of hydraulic components. In the standard variant, a hybrid cooler with predominantly dry cooling is used.

A monitoring system and an Internet-based display of the measurement data were included in all systems. Automated analysis of the measured data was the pre-requisite for system optimisation and error detection during operation. The last system was taken into operation in Freiburg in the summer of 2013 (Figs. 1 and 2). Analysis of the data confirms that it is operating well, with thermal coefficients of performance for the chiller in the expected range; the maximum value in the frequency distribution is between 0.4 and 0.55.

The project experience showed in several cases that – regardless of the degree of hydraulic simplification – inadequate dimensioning of the cooling and heating distribution network on the operator's side leads to incorrect adaptation in system operation. For optimal usage of solar cooling, it is thus imperative that the load loop be carefully dimensioned.

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

www.solcoolsys.de



CONCENTRATOR OPTICS: FROM DESIGN TO PRODUCT

A large share of the investment costs for concentrating solar thermal systems is due to the reflectors. Costs can be reduced by the use of reflectors manufactured as composite-surface elements, such as are used e.g. in the car-making industry. These are self-supporting, featuring high internal stiffness and intrinsically low weight. Large components with curved surfaces can also be manufactured industrially. At present, the production of components that are strongly curved in two directions, such as are needed for Stirling dish systems, presents a particular challenge. In an industrial project, we are supporting a manufacturer of composite reflectors in the development of dish prototypes by design optimisation and quality tests.

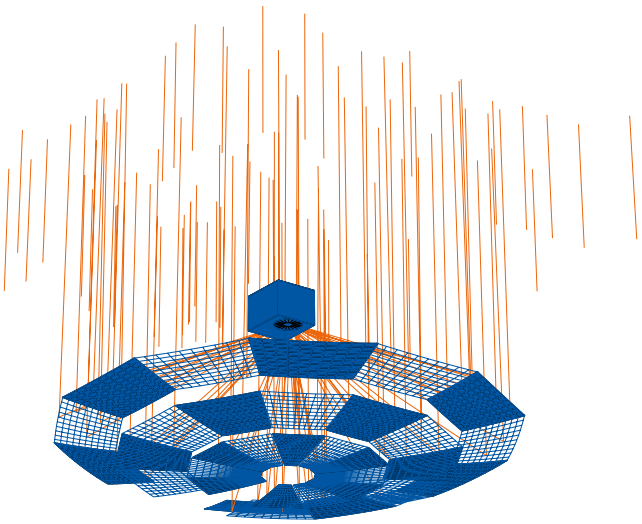
Gregor Bern, Anna Heimsath, Peter Nitz, Werner Platzer

In the development of a novel manufacturing process for concentrators consisting of composite elements, we are supporting our industrial partner with optimisation, experimental characterization and expertise. Thin glass mirrors are attached with adhesives to the curved, self-supporting, layered structure with high intrinsic stiffness. The manufacturing process makes large-area, facetted elements feasible, which are simultaneously light-weight and structurally stable.

Stirling dish systems combine a concentrator in the form of a parabolic dish with a Stirling motor to generate electricity. The dishes have a high concentration factor and the potential for high efficiency, but require great precision and optimised interaction between the components. With our "Raytrace3D" simulation tool, we investigate the geometrical configurations of concentrators and optimise them by ray tracing, introducing product parameters as boundary conditions. The novel design greatly reduces the optical losses which can arise due to manufacturing tolerances and positioning inaccuracy (Fig. 3).

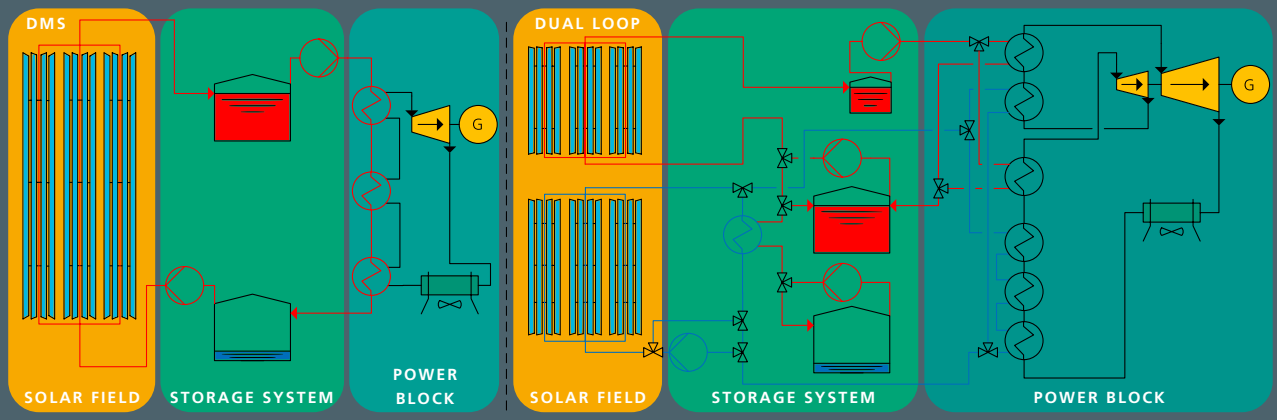
1 *In the fringe reflectometry laboratory, we test the form stability of small and also large reflector prototypes with high spatial resolution.*

2 *Different samples of composite reflectors are tested in climatic chambers for durability and thermal deformation.*



3 *Dish concentrator for Stirling dish systems: Result of simulation and optimisation with ray-tracing programs.*

For product and quality control, we carry out tests in climatic chambers (Fig. 2) to investigate the stability of the composite joints. We apply fringe reflectometry (Fig. 1) to characterize the form stability of prototypes. With this measurement, the deviation of sight rays is determined after reflection by the facets. In this way, we can identify local deviations from the ideal form with high spatial resolution, and draw conclusions on potential for improving the production process.



1

STORAGE TECHNOLOGY FOR LINEAR FRESNEL POWER PLANTS

In contrast to PV power plants, solar thermal power plants can also supply electricity as required during periods with little or no solar radiation due to the integration of thermal storage units. Different storage solutions are appropriate for different types of collectors. We have investigated various storage technologies and power plant concepts for linear Fresnel collectors and compared their levellised costs of electricity to those of a modern reference power plant (parabolic trough power plant with an indirect storage system).

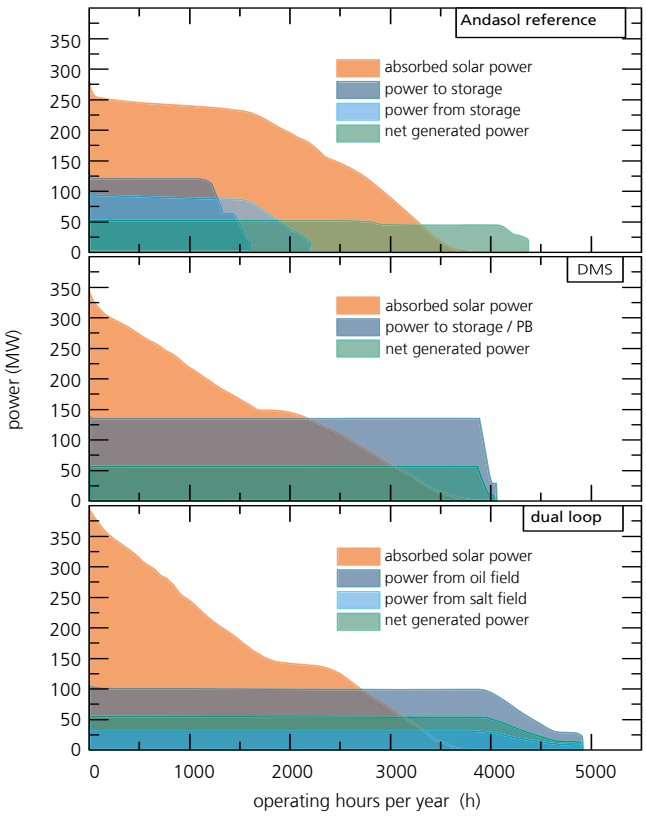
Tom Fluri, **Alexander Vogel**, Werner Platzer

1 *Schematic diagram of a direct molten salt power plant (left) and a dual-loop power plant (right).*

A reference system was compared to a direct molten salt (DMS) power plant with direct storage in two tanks (Fig. 1, left), and a dual-loop power plant, consisting of a combination of thermal-oil and molten-salt solar fields with an indirect/direct storage system (Fig. 1, right). The reference design is based on that used in the Andasol power plants in Guadix, Spain. For each power plant design, the optimal number of loops to achieve the lowest levellised cost of electricity (LCOE) is determined by calculating the annual yield. As a result, the net annual electricity yield varies from case to case. Each of the power plants included a 1000 MWh_{th} molten salt storage unit and a 50 MW_{el} power block. The "ColSim-CSP" software developed by Fraunhofer ISE was used for the simulations.

Fig. 2 presents the power versus the operating hours per year for the reference, DMS and dual-loop power systems located in Daggett, USA. The lowest LCOE for the assumed parameters is achieved with the dual-loop concept. The direct molten salt concept also achieves low LCOE, is less complex and is best suited to providing power flexibly. If the costs of the solar field and the heat exchanger system could be reduced by about 15%, the direct molten salt concept could present the best option.

The "Supergrid" project was supported by the Fraunhofer-Gesellschaft within the "Märkte von Übermorgen" (Markets for Tomorrow) Programme.



2 *Simulated power versus operating hours per year for the reference, DMS and dual-loop power plants located at Daggett, USA; the plateau at 150 MW indicates that more solar power is available than can be stored with a fixed storage capacity of 1000 MWh_{th}.*

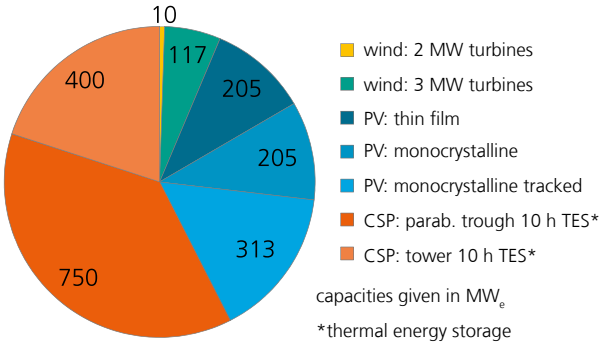
1

TECHNOLOGY MIX OPTIMISATION FOR A SOLAR AND WIND PARK IN KUWAIT

In Kuwait, an energy park with wind, CSP and PV technology and a total capacity of 2 GW is to be built in three phases over an area of 100 km². A total of 14 potential technologies were selected and evaluated techno-economically in a study. In order to obtain the optimal technology mix for different scenarios, we defined evaluation criteria and developed an optimisation procedure. One important goal is to meet the pronounced peak loads in Kuwait with the park. The optimisation takes account of not only technological but also socio-economic factors, as well as a predicted cost development up to the final expansion phase in 2030.

Thomas Fluri, Verena Jülch, **Simon Lude**, Werner Platzer

1 *Model of the 2 GW solar / wind park "Shagaya" in Kuwait.*



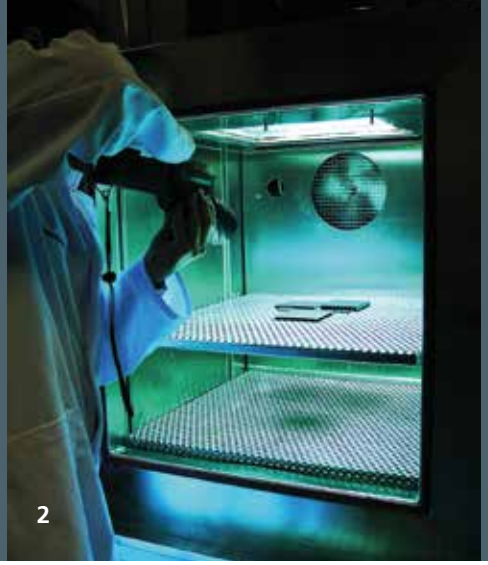
2 *Distribution of renewable energy technologies in the Shagaya energy park based on the simulations for the optimisation study. The primary goal resulting in this mix was electricity supply during peak load periods.*

The study began with technology screening to identify solar and wind technologies which were potentially suitable. The result was a selection of 14 different technological options (3x wind, 5x PV, 6x CSP). Time series for the energy yield over a year were calculated for these options with suitable simulation tools, cost models were prepared and further rating factors such as water consumption and stimulation of employment within the country were determined.

In a cost-benefit analysis, the technology mix options were evaluated according to seven criteria. By assigning different weights to the individual criteria, it was possible to optimise the quantitative composition of the technologies in the park with respect to a single primary goal. Three different scenarios with a focus on generating electricity during peak load periods, a high total annual electricity yield and a low levellised cost of electricity respectively were analysed. 2010 was defined as the reference year for both load and meteorological data.

As boundary conditions for the optimisation, not only the available area and the target capacity of 2 GW were set but also the minimum capacity credit to be achieved – the ratio of newly installed renewable capacity to conventional capacity which it replaced. Based on the optimisation results and after consultation with the Kuwait Institute for Scientific Research, the recommended technology mix consists of 127 MW of wind energy, 723 MW of photovoltaics and 1150 MW of concentrating solar power plants with thermal storage (Fig. 2).

1



2

POLYMER ANALYSIS FOR FUTURE SOLAR THERMAL TECHNOLOGY

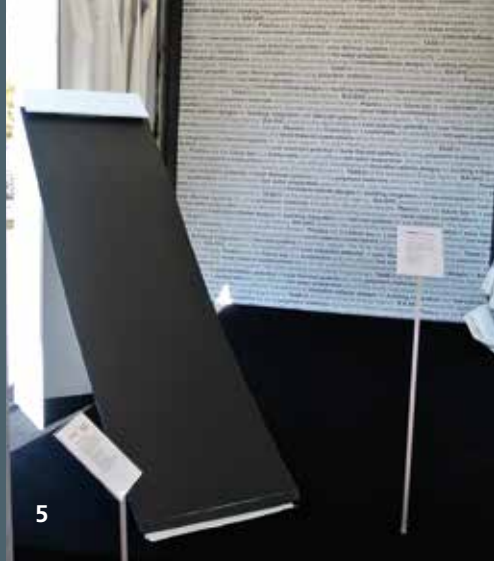
Rising prices for raw materials, complex production processes and a growing demand for cost-effective "Plug and Play" systems are presenting major challenges to the solar thermal sector. New designs and manufacturing processes are desired, which can become feasible by the use of optimised polymers, for example. Polymers present a large cost-reduction potential and also offer the opportunity to "rethink" solar thermal technology due to new design freedom. At Fraunhofer ISE, the suitability of new materials is tested in the durability analysis group, which develops appropriate tests and characterization methods for polymers and validates them on the basis of real exposure data.

Steffen Frick, Michael Köhl, Andreas Piekarczyk, Sandrin Saile, **Karl-Anders Weiß**, Regine Weiß, Harry Wirth

Polymers are light, can be formed flexibly and are suitable for efficient mass production. In order to take advantage of these properties in solar thermal technology, it is necessary to test polymers with respect to their suitability for application in solar thermal systems. Depending on the component type, the materials must withstand high operating temperatures and pressures and/or exposure to UV radiation. Fraunhofer ISE is developing appropriate testing sequences and accelerated aging tests to optimise new materials. Within the "SCOOP" and "ExKoll" projects and the "IEA SHC Task 39", an international platform for work on polymer-based solar thermal systems, the durability analysis group is active in developing new materials and designs for cost-effective and efficient polymer-based collectors.

To investigate the materials, a combined approach is adopted, consisting of non-destructive optical methods (ATR-IR, FT-IR and Raman spectroscopy), surface-sensitive analysis (AFM) and mechanical procedures. The samples are analysed after accelerated aging by exposure in climatic chambers to high temperatures in combination with UV radiation, and also high humidity in some cases. To determine the aging parameters, the Institute can draw on comprehensive exposure data sets from its own outdoor test sites, including those in Freiburg (temperate climate), on Gran Canaria (maritime) and in the Negev Desert (arid) (Fig. 1). The extracted data can also be used to optimise materials for the different application areas for solar thermal collectors.

In addition, the materials are tested with respect to the intended manufacturing technology. Within the European "SCOOP" project, extrusion and injection moulding are being



investigated as production technology. Whereas current work is concentrating on materials testing with standard tensile strength tests, further tests are being developed which are closer to the product stage, e.g. indentation tests for extruded multi-wall panels. By correlating these with spectroscopic data, conclusions concerning molecular processes can be drawn from the mechanical changes (Fig. 3).

The results are input directly into design development. The most recent result of this work is a thermosyphon system concept with a collector based on polypropylene. The prototype has a collector area of 1.2 m² and a storage capacity of 65 l, and was presented at the "Task 39" exhibition in September. The collector can be produced cost-effectively by extrusion and is considered to be a promising product for export to sunny areas such as the MENA region.

The great potential of this region was revealed by a market analysis in the "ExKoll" project. The aim of the study was to identify countries which potentially offer high potential for collectors made of polymers. In order to ensure the relevance of the results, an economic feasibility study is currently being carried out for different collector concepts. These are compared to each other on the basis of life cycle analyses and evaluated with respect to established collector concepts.

Both the "ExKoll" project and participation in the "IEA-SHC Task 39" are supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). The "SCOOP" project is funded within the 7th Framework Programme of the European Union (EU).

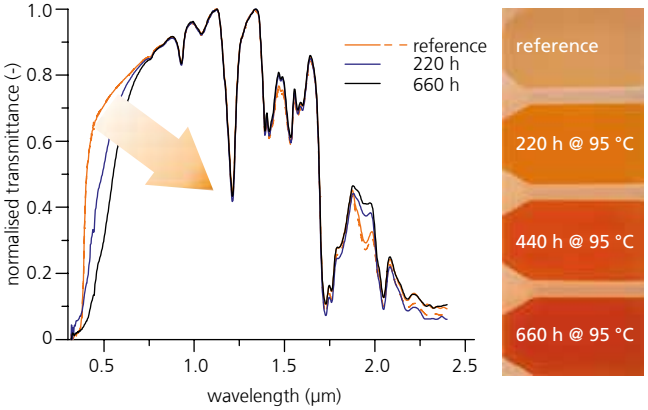
1 *Polymer collector exposed on the maritime outdoor test stand in Pozo Izquierdo, Gran Canaria.*

2 *Scientists from Fraunhofer ISE investigating the suitability of polymers for application in solar thermal systems.*

3 *Indentation test of an extruded multi-wall panel.*

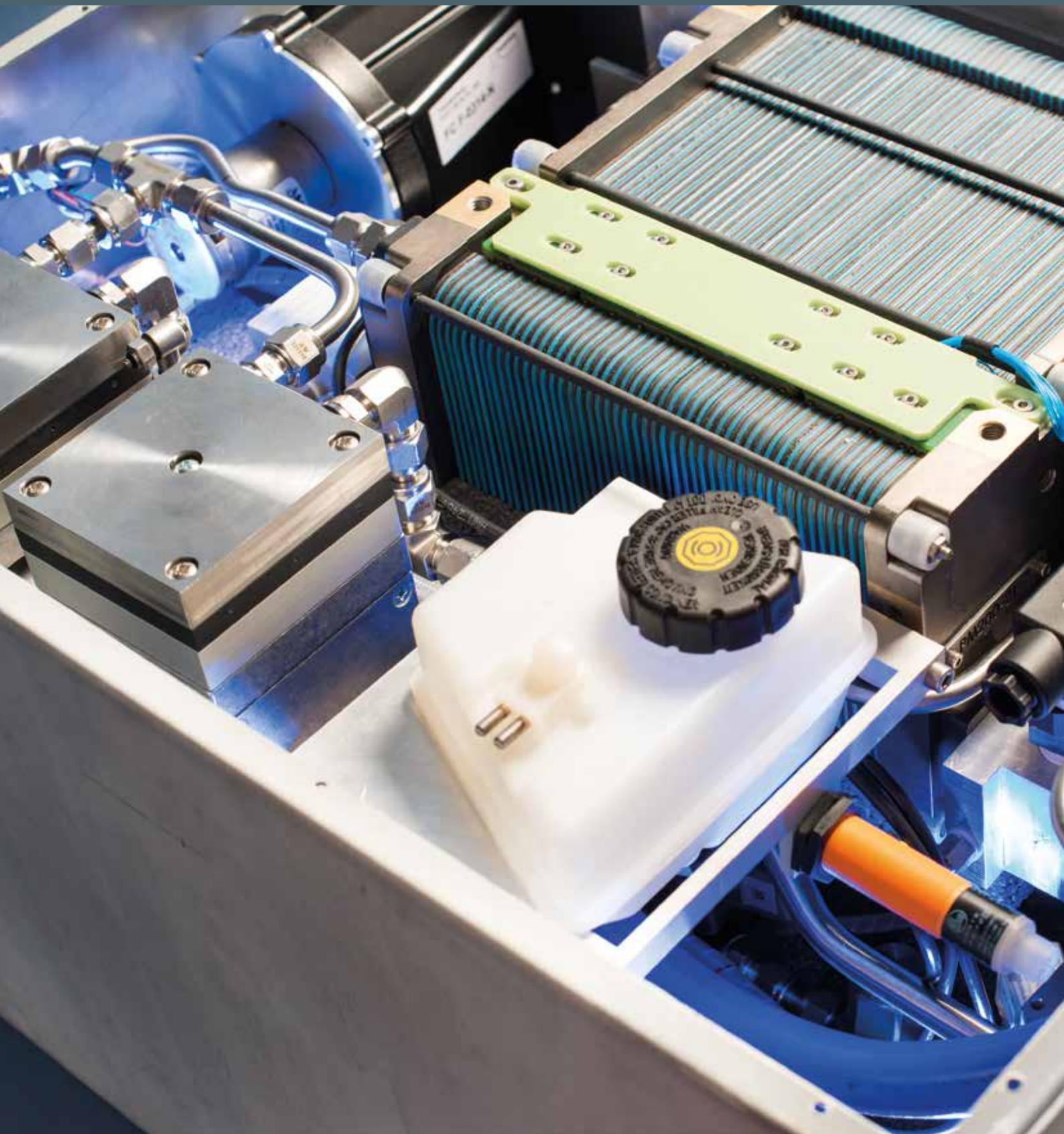
4 *Standard tensile strength test according to ISO 527.*

5 *Prototype of a thermosyphon system made of polymers at the Task 39 Exhibition in Freiburg, Germany (Design: SCOOP, Construction: Fraunhofer ISE).*



6 *Optical characterization of the discoloration of polyamide test samples due to formation of chromophores during dry heat aging at 95 °C.*

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 carrier which possesses the potential to store large amounts of energy also over long periods of time in a chemical form. Apart from the option to generate electricity again in stationary fuel cell systems or gas-fuelled turbines, hydrogen also forms a link to zero-emission mobility as a fuel for fuel cell vehicles. In future, water electrolysers will represent a valuable control option for city utilities or grid operators to quickly adapt electricity generation to consumption and thus stabilise the grid frequency.

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. We carry out multiphysical simulation of cells and stacks. In addition, we construct functional product models from the cell stack up to fully automated complete systems for pressurised operation up to 50 bar. We operate test stands for cell stacks up to 1 MW_{el} for the final stage of these developments. Furthermore, 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 for drive units, for decentralised 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 gained experience over many years 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 synthesise liquid fuels or chemical building blocks, which were previously derived from oil, out of hydrogen and carbon dioxide. Within experimental investigations or studies, we assess the technological feasibility of new, energy-efficient and resource-conserving processes.

Our research spectrum concerning electrochemical conversion technology and chemical engineering processes is facilitating the transition from the utilization of fossil energy carriers to a sustainable, zero-carbon energy economie.

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 control technology for laboratory systems, prototype systems and functional models
- production technology
- technological, concept and user acceptance studies

FURTHER INFORMATION

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Hydrogen-based fuel cell system with an output power of 1.5 kW for seasonal energy storage.

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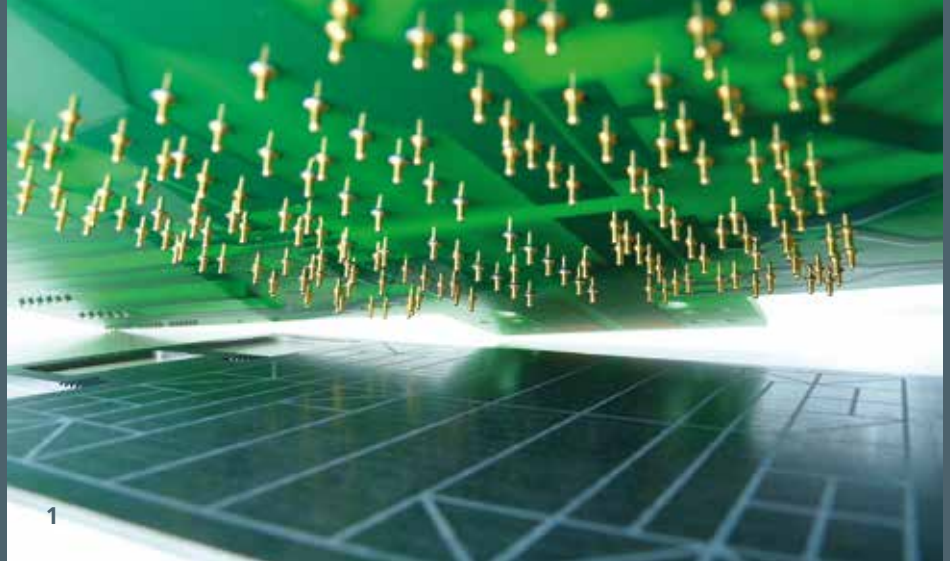


1

SPATIALLY RESOLVED CHARACTERIZATION OF AUTOMOTIVE FUEL CELLS

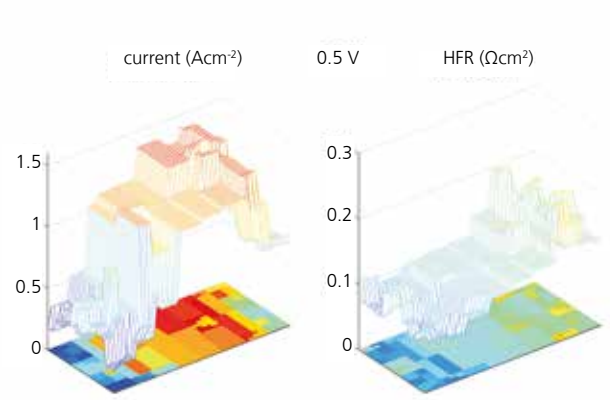
Now that fuel cell technology has proven its potential in numerous test vehicles of many international car manufacturers over many years, it is planned to commercialise it in mass-produced vehicles by 2020. However, in order to reach the cost targets, several technological breakthroughs are still needed. To achieve this, detailed understanding of the strongly coupled electrochemical and thermodynamic processes in a fuel cell is needed. Five leading institutions are contributing their expertise in the "GECKO" research project to investigate the complex processes, such as two-phase transport or degradation processes.

Robert Alink, **Dietmar Gerteisen**, Ulf Groos, Thomas Jungmann, Janina Löffler, Sebastian Prass, Nada Zamel, Christopher Hebling

Fraunhofer ISE is analysing the inhomogeneity which occurs at the cell level both in stationary and dynamic operation with the help of segmented fuel cells and a unique multi-channel characterization system. The optimisation potentials for design, materials selection and operating strategies are derived from this analysis.

Automotive fuel cells have cell areas of up to 400 cm². With current densities of up to 3 A/cm², appreciable depletion of the reaction gases accompanied by simultaneously increasing humidity is the result. These can cause inhomogeneity which can greatly affect performance or cause degradation. In order to locally characterize the operating state of the cell up to a total current of 780 A, we are equipped with a system containing 68 synchronously operating potentiostats. It allows us to measure both current generation and electrochemical impedance at different frequencies with high spatial resolution. The spatially resolved characterization in combination with

1 *A current-conductor plate based on printed circuit board technology contacts a segmented gas flow-plate of graphite via spring-loaded contact pins.*

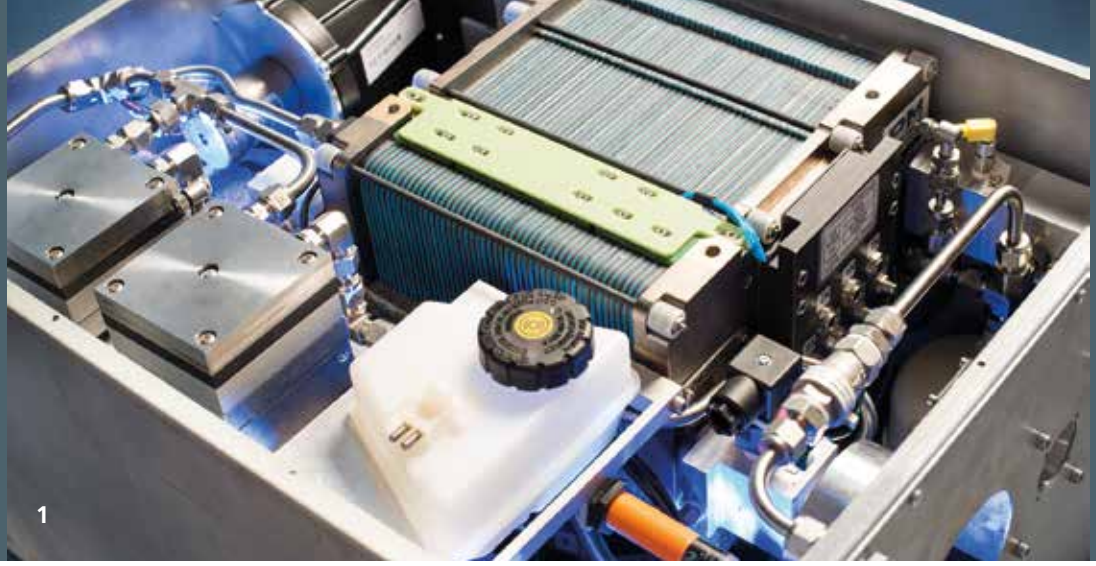


2 *(left) The current density distribution of a 200 cm² cell reveals low current generation near the gas inlet and the gas outlet, for measurements made with a cell voltage of 0.5 V and a stoichiometry of 2.2 : 2.3 (H_2 : air). (right) The locally measured high-frequency resistance (HFR) identifies membrane dehydration and thus raised ohmic losses near the gas inlet.*

modelling work at the cell level enables us to unravel the complex interaction between processes caused by inhomogeneity. For instance, we can separate the loss mechanisms with regard to their time constants. The resulting knowledge at the cell level is transferred within the "GECKO" project to the stack level and correlated with single-cell impedance spectra measured simultaneously in the stack.

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

www.gecko-fuelcell.com

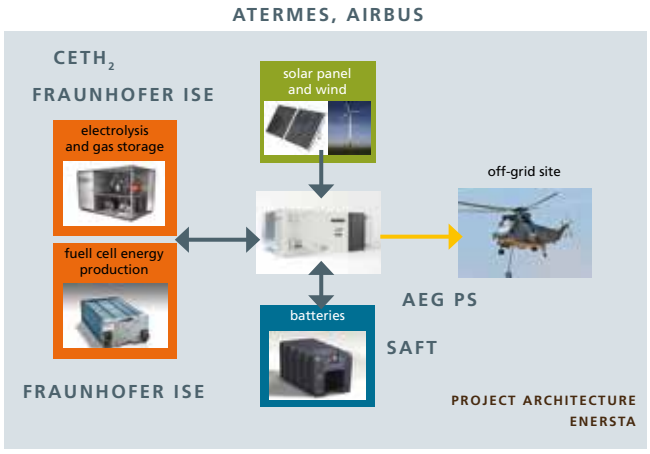


AUTONOMOUS FUEL CELL SYSTEM FOR TELECOMMUNICATIONS

A modular, autonomous power supply for the power range from 1 to 5 kW is being developed as part of the "Enersta" joint project. Depending on the location, this can connect different electricity generators (photovoltaic, wind, fuel cell) with storage systems (battery, hydrogen generation and storage) and the electricity consumer. Different power ratings or capacities for all components can be accommodated. A hydrogen-based fuel cell system is being constructed as a central component which allows seasonal energy storage. Our goal is to develop an energy-optimised fuel cell system which can be used in ambient temperature conditions from well below 0 ° to above 40 °C.

Gerrit Ammon, Ulf Groos, Stefan Keller, **Wolfgang Koch**, Christopher Hebling

1 *1.5 kW fuel cell system from the "Enersta" project.*



2 *Responsibilities of the "Enersta" project partners: AEG is responsible for the overall controls, Saft for the storage battery, $CETH_2$ for electrolysis and H_2 storage, Atermes for the cabinet, Airbus for the simulation tool and the complete solution and Fraunhofer ISE for the fuel cell system and the H_2 storage.*

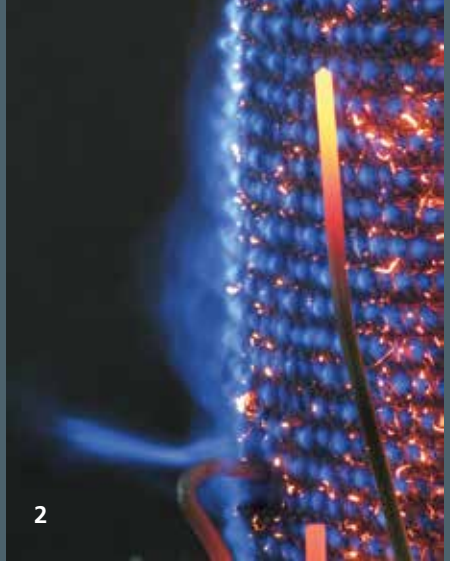
The modular power supply was dimensioned on the basis of a yield simulation for the location of Elancourt, near Paris, and is intended to generate net power of 1 kW throughout the year, 24 hours a day, to supply a telecommunications station with electricity. Wind generators and photovoltaic modules charge a storage battery, to which the load is connected. When excess energy is available, hydrogen is generated by electrolysis and temporarily stored in three individual tanks at 30 bar. As soon as the state of charge of the battery falls below a set value, the fuel cell switches on and charges the storage battery to a pre-defined state of charge.

A fuel cell system with an output power of 1.5 kW is needed to ensure an uninterrupted power supply. We are developing an efficiency-optimised system, based on a fuel cell stack which is commercially manufactured by Proton Motor Fuel Cell GmbH. In designing the system, aspects such as the ability for cold starts, low energy consumption of the system components and ease of assembly were taken into account.

Degradation of the fuel cell stack is reduced by an optimised strategy for starting and stopping stack operation. We test the system itself and the operation management system for functionality under extreme weather conditions from -20 °C to +60 °C in our climatic chamber and are preparing for the test phase of the system, which should start in 2014.

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

www.h2-ise.de



NEW EVAPORATION PROCESS – CLEAN FUTURE FOR OIL HEATING

The primary energy demand to supply energy to buildings is sinking due both to improved thermal insulation and also to increasing application of solar thermal systems or ventilation systems with heat recovery. The lower heating demand is stimulating the demand for modulating heating systems which can meet the constantly high power demand for domestic hot water and the low power demand to provide heat for space heating. However, the construction principle of conventional oil-fuelled burners means that they cannot be modulated. Thus, we have cooperated with the industrial partners, Herrmann GmbH & Co. KG, Solvis GmbH & Co. KG, Elster GmbH and Umicore AG & Co. KG to develop an oil vapour burner which features efficient combustion, can be modulated and simultaneously reduces emissions.

Thomas Aicher, **Robert Szolak**, Christopher Hebling

The core of the oil vapour burner is a catalytic process developed at Fraunhofer ISE, which can evaporate heating oil and other liquid hydrocarbons without any residues. When the fuel is evaporated, an appreciably better mixture with air for combustion can be prepared. Formation of this mixture is a decisive criterion for the combustion quality. Poor mixing leads to higher emissions of nitrogen oxides, carbon monoxide, hydrocarbons and soot. The evaporator unit is integrated simply before the burner. With this unit, heating oil can burn in gas burners efficiently and with low emissions. In addition, the existing, cost-effective system configuration from gas combustion can now also be used for oil.

1 *The new evaporation process for liquid fuels improves mixing and can be applied in many different ways, e.g. for new burner concepts, to generate gas in fuel cell systems, for turbine technology and for motor processes.*

2 *A gas burner operated with oil vapour. The blue flame colour indicates that combustion of the oil vapour produces little emission, just like gas.*

Initial investigations at Fraunhofer ISE on gas burners from Solvis and Herrmann demonstrated that the emission values over the complete modulation range from 5 to 15 kW thermal power lie below the prescribed limits. The wide modulation range contributes to this effect, as the number of starts for the burner is reduced considerably. Furthermore, the emission of nitrogen oxides is reduced compared to conventional oil burners. The burner operation complies with both the DIN EN 267 standard and the first German emission control ordinance. The oil vapour burner is also suited for use in living rooms, as it is quieter than a normal oil burner.

The research project will run until the end of 2014 and serves to develop a prototype as a preliminary step toward product development. The project is supported by the German Federal Ministry of Economics and Energy (BMWi).

SYSTEM INTEGRATION AND GRIDS – ELECTRICITY, HEAT, GAS

The transformation of the German energy system into a carbon-free 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 various 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 liberalised energy market. In the "E-Energy Programme" of the German Federal Government, Smart Grid technology was investigated with a focus on the information and communications technology (ICT) systems. Fraunhofer ISE studied the integration of decentralised generators in a regional energy market within the "eTelligence" project.

Integration of the electricity and heating sectors allows compensation of the greater fluctuations in the electricity grid which arise due to the input from renewable energy sources. For example, electricity generation by electricity-heat-led combined heat and power (CHP) systems can be shifted into the evening peak load period, or the conversion of excess electricity into heat by heat pumps and electric immersion heaters can be used. The 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 optimise the operation of electricity generation on the basis of spot market prices and weather predictions with the help of thermal storage buffers.

The research of Fraunhofer ISE concerning neighbourhood concepts focusses on heat distribution grids which enable CHP systems and thermal storage to be integrated. The goal is to develop an optimisation 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 address a still wider field. They aim for holistic optimisation of the entire urban space by adapting the supply structure and mobility concept to the requirements of renewable energy supplies. Concepts for the city of the future are being developed for the first time within the Fraunhofer "Morgenstadt" Programme.

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 analysed. They are also used to develop communications and control systems for the components and operation management technology. R&D work is concentrating on decentralised 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 decentralised 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 the power-to-gas technology, hydrogen is generated by electrolysis for decentralised storage or input into the existing network. At Fraunhofer ISE, a solar hydrogen filling station was taken into operation, which demonstrates that all of the components needed to use hydrogen for zero-emission mobility are already available today.

WEITERE INFORMATIONEN

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The infrastructure of the SmartEnergyLab allows system providers to test and evaluate both their individual systems and also complete concepts in a realistic environment.

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2

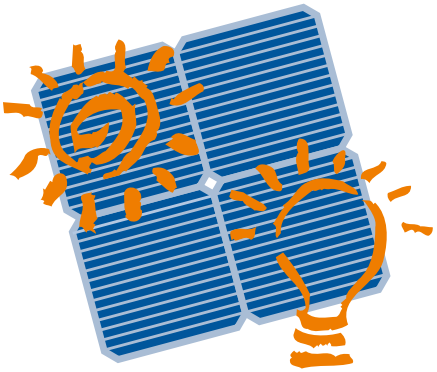
DEVELOPMENT OF RURAL REGIONS BY DEPLOYING PHOTOVOLTAICS

Due to its 30 years of experience in off-grid power supply, Fraunhofer ISE is representing Germany in Task 9 on „Deploying PV Services for Regional Development" in the "Photovoltaic Power Systems Programme (PVPS)" of the International Energy Agency (IEA). Task 9 has the goal of disseminating knowledge on the importance of photovoltaics as a technically relevant and cost-effective technology to generate electricity in developing countries. Fraunhofer ISE can make essential contributions overseas to imparting knowledge on renewable energy by this international cooperation and, in return, gains insight into new technological and economic developments in other countries.

Adnan Al-Akori, **Georg Bopp**, Fabian Himmelsbach, Brisa Ortiz, Norbert Pfanner, **Friedemar Schreiber**, Matthias Vetter, Günther Ebert

1 *Solar-powered LED lamp, a typical Pico PV-System.*

2 *A young fisher cleans the PV module of a Pico PV-System in the coastal region of southern Yemen.*



In addition to Germany, which is represented by Fraunhofer ISE, the countries of Denmark, Sweden, Switzerland and Japan are participating in the work of Task 9 under the leadership of France. The working group is addressing the topics of "Access to Modern and Sustainable Electricity Services" and "Effective Application of Photovoltaics and Renewable Energy in Developing Countries". The activities concentrate on the dissemination of information on energy supply systems with a focus on photovoltaics for village power supplies (drinking water supply, health centres, small lighting systems and integrated communications solutions), photovoltaics in mini-grids and hybrid systems, integration of photovoltaics in urban areas, large photovoltaic power plants and innovative business models. Experience is disseminated in the target countries by preparing handbooks and publications, and carrying out training seminars.

The experts from the represented countries actively exchange experience in regular project meetings and workshops. Fraunhofer ISE made major contributions to the handbooks entitled "Pico Solar Systems for Remote Homes" and "Rural Electrification with PV Hybrid Systems", as well as a guideline on design and simulation of PV hybrid systems. Furthermore, Fraunhofer ISE is leading the preparation of a handbook on experience in health centres with PV power supplies. The information is transferred to representatives from developing countries by web seminars or workshops such as that held in Myanmar in March, 2013.

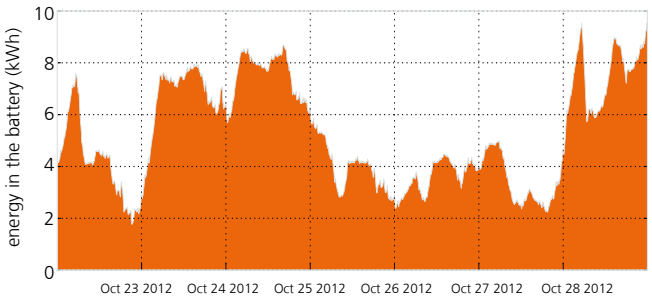
The project is funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB).

OPPORTUNITIES AND CHALLENGES OF SOLAR BATTERY SYSTEMS

Net parity of photovoltaic electricity with the price for domestic consumers makes on-site consumption of locally generated electricity increasingly interesting. Efficient and long-life batteries will allow storage to increase on-site consumption in future. However, as the prices for battery systems are still high, it is useful to tap new sources of income to increase the economic viability of batteries and thus gain the greatest possible benefit for the energy system. In the "Net-PV" project, we are investigating the opportunities and benefits of different operating strategies for solar battery systems and the combination of innovative business models.

Georg Bopp, Martin Llerena Engesser, Thomas Erge, **Raphael Hollinger**, Bernhard Wille-Haussmann, Christof Wittwer, Günther Ebert

In the „Speicherstudie 2013" (Storage Study 2013 – Short survey report to estimate and evaluate energy-relevant, economic and other effects of supporting building-installed electrochemical storage units), it was proven that decentralised storage of PV electricity can stabilise the grid. In the "Net-PV" project, we are investigating the outlook for economic application of solar battery systems after termination of the Renewable Energy Act and introduction of support for solar battery systems (which came into force on 01.05.2013). Different business models and their combination were analysed to this purpose. The core element is control reserve power – for which the transmission grid operators call for tenders to maintain frequency stability under regelleistung.net – in combination with peak load reduction of a local or regional grid with respect to the next higher-order grid. In addition to income from provision of control reserve power, this leads to maximisation of the bonuses for avoided grid transmission charges and to increased on-site consumption. It thus represents an economically extremely interesting combination of business models. Initial simulation results (Fig. 3) confirm the potential of combining the three business models. In 2015, an extensive field test will follow in the grid operated by the town utility Schwäbisch Hall, in which the provision of primary control reserve power by decentralised solar battery systems in private households will be implemented in practice for the first time.

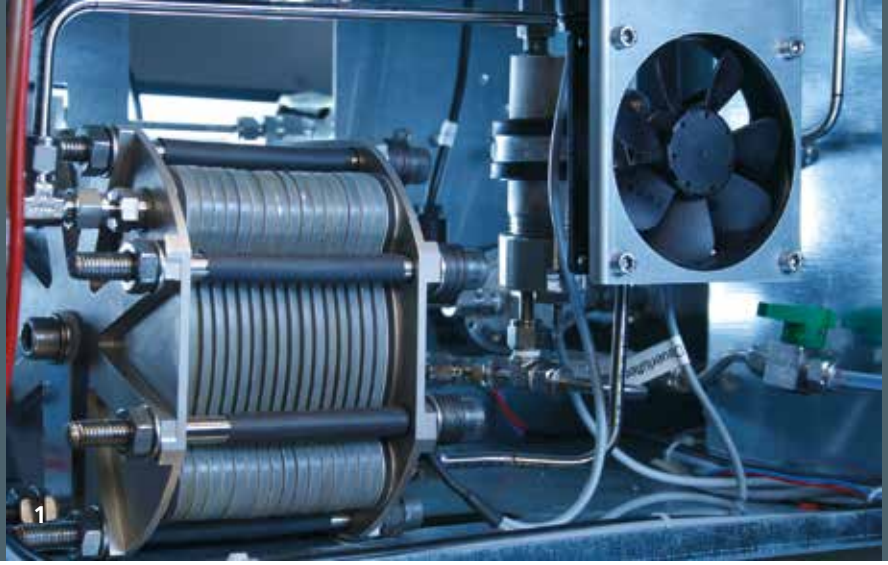


3 *Example of the energy profile for the battery of a free-standing house with a PV system, which not only increases the amount of PV electricity consumed on site but also provides primary control reserve power as a service to the transmission grid operator. The two business models complement each other and enable the battery to be operated economically.*

1 *Grid services can be provided to an increasing extent by the distribution grid.*

2 *Newly developed concepts are implemented and tested in the SmartEnergyLab of Fraunhofer ISE.*

The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB) and the industrial partners, Stadtwerke Schwäbisch Hall, Saft Batterien GmbH, E3 – Energie Effizienz GmbH, KACO new energy GmbH and IDS GmbH.



EFFICIENT OPERATION MANAGEMENT OF ELECTROLYSERS IN POWER-TO-GAS SYSTEMS

Hydrogen is a promising form of secondary energy, which can be used in future for a wide range of applications. As it can be generated on a large-scale and CO_2-neutral basis by electrolysis of water, electrolysers are key components in the so-called power-to-gas (PtG) concept. Integration of these hydrogen generators into the energy system calls for fundamental understanding of such units. We realistically model the operating behaviour of different electrolysers and power-to-gas systems by stationary and dynamic system simulations and investigate technical and economic scenarios for operation management and system integration.

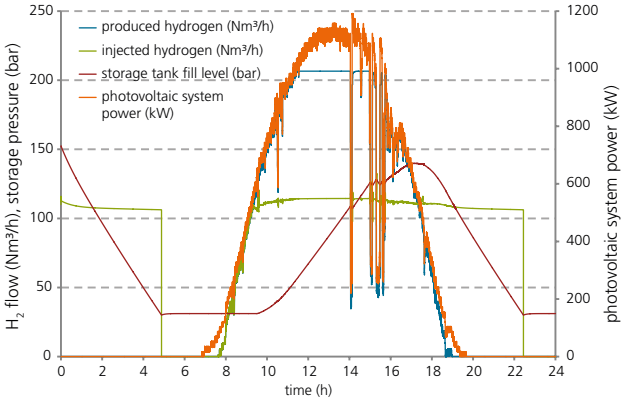
David Müller, **Tom Smolinka**, Christopher Voglstätter, Arne Raphael Werner, Christopher Hebling

The continual expansion of renewable energy systems increases the need for options to control the electricity grids flexibly and safely and to store electricity. The power-to-gas concept combines the approaches of active load and generation management with the idea of storing electricity from renewable sources temporarily as chemical energy. When excess electricity is available, it is used in electrolysers to split water into hydrogen and oxygen. The generated hydrogen can be stored temporarily and / or injected into a gas distribution network, to be used later as required in different applications (e.g. mobility, electricity generation, chemical industry).

Fig. 2 shows an example for the dynamic behaviour of a PtG system (rectifier, electrolyser, gas purification and drying, compressor, storage buffer and injection valve) which follows the feed-in profile of a PV system. The PEM pressurised electrolyser simulated here is easily able to respond to the daily profile of the PV system. The storage buffer is used to adapt the hydrogen injection to the load curve of the natural gas pipeline. With the help of the simulation tool, we are able to carry out a comprehensive technological analysis and to do preliminary dimensioning of such systems. In further work, the technical simulation will be connected to market models so that various business models can be considered and evaluated.

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

1 *The core of a power-to-gas system is the cell stack for electrolysis, in which hydrogen is generated electrochemically. To validate data, we measure laboratory systems or use data from field tests. The photo shows a membrane cell stack for pressure electrolysis developed at Fraunhofer ISE.*



2 *Dynamic behaviour of a PtG system with a pressurised PEM electrolyser which responds to the power profile (orange) of a photovoltaic system. The generated hydrogen (blue) is temporarily stored under pressure (red) and injected into a natural gas pipeline (green) as required. For clarity, only a constant injection capacity is assumed.*

INTEGRATED ENERGY CONCEPTS FOR CITIES AND NEIGHBOURHOODS

The urban space is a primary location for transforming the energy system. In addition to reducing the energy demand of buildings by renovating the existing building stock, transformation of the urban energy supply systems is necessary. Evaluation and planning methods are being developed at Fraunhofer ISE to support and accompany this transformation process. Within the Fraunhofer-funded "Morgenstadt City Insights" project, transformation processes from cities around the world were subjected to interdisciplinary analysis. In the "Energiequartier Haslach" pilot project of the city of Freiburg, Germany, Fraunhofer ISE is developing target scenarios for the development of the energy system of this suburb.

Jörg Dengler, Arnulf Dinkel, Jan-Bleicke Eggers, Sebastian Gölz, **Sebastian Herkel**, Sattaya Narmsara, Dominik Nören, Gerhard Stryi-Hipp

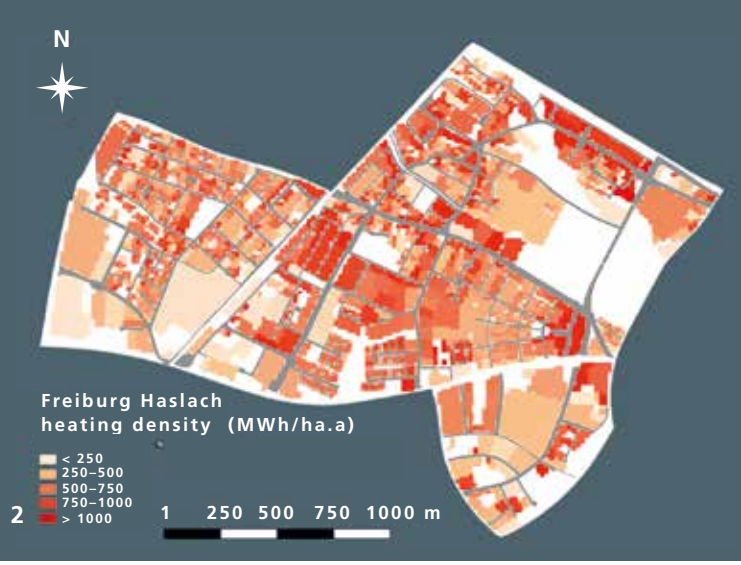
m:ci Morgenstadt City Insights

Within the "m:ci Morgenstadt City Insights" project, involving more than 30 partners from business and municipal authorities from around the world, six cities including Tokyo, Copenhagen, Singapore and Freiburg are being evaluated during their transformation processes toward greater sustainability. Fraunhofer ISE is coordinating work on the energy sector. The basis for analysing the municipal strategies to transform the energy system was the development of suitable indicators. The most important indicator is the end energy consumption per capita. The central indicator for progress toward a sustainable energy system is the proportion of renewable energy in the total energy demand.

Availability of statistical data on the emissions caused by the energy sector is decisive for controlling the success of energy politics. The European cities of Freiburg, Berlin and Copenhagen have established corresponding mechanisms to this purpose. The analysis of practical examples in Freiburg, Copenhagen, Singapore and Tokyo shows that the target energy systems differ considerably according to the local conditions and also that the routes to achieve them must be defined individually. However, the basic concepts are similar both with respect to the technology which can be applied and also the necessary processes. High efficiency in conversion and distribution, reduction of the energy demand with a particular focus on energy-efficient buildings, complete exploitation of the local potential for renewable energy sources and cooperation with the surrounding region to achieve wider usage of renewable energy are all important components.

The analysis reveals that implementation can be successful if clear goals are defined, a systematic approach is followed and effective municipal structures exist to monitor progress towards the goals and adapt these goals if necessary. In addition, "lighthouse projects", the involvement of all relevant players and sustainable implementation of smaller projects are also important factors for success. Fig. 3 illustrates an analysis of interactions between goal definition, implementation and monitoring. It also indicates options for action by municipal authorities and industrial partners to implement energy transformation at the local level and develop appropriate business models.

1 *Freiburg im Breisgau, Germany is one of the six cities around the world which are being analysed with regard to their transformation processes toward more sustainability within the project entitled "m:ci Morgenstadt City Insights". Fraunhofer ISE is coordinating the investigations on the energy sector in this project.*



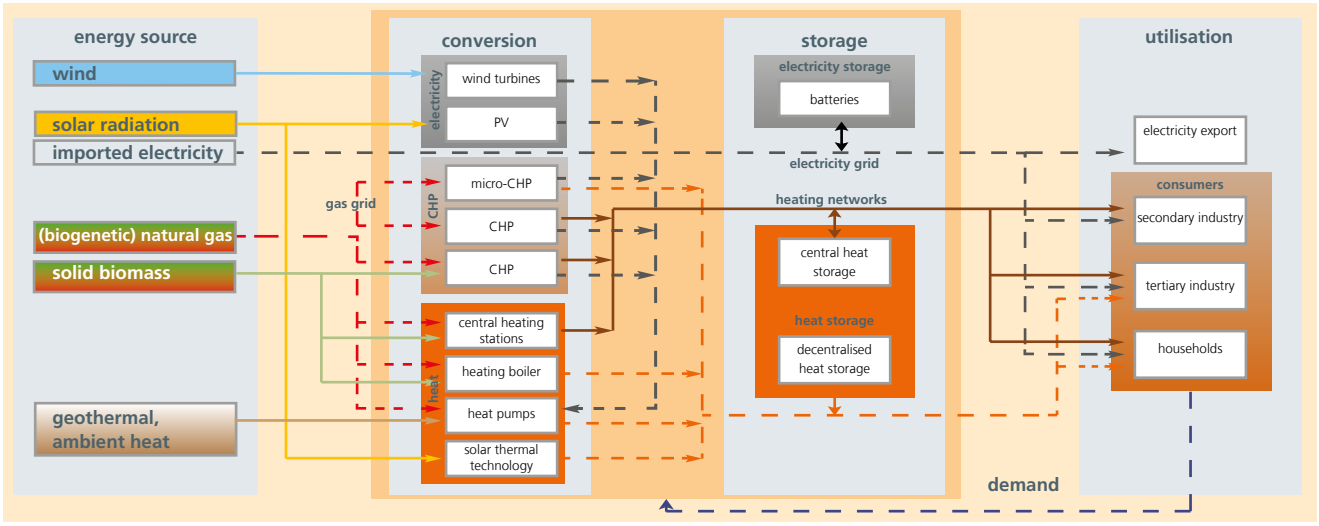
2 *"Energiequartier Haslach": Based on the density of the heating demand and electricity load profiles, supply scenarios for heating and electricity are developed and optimised. When combined with the potential of renewable energy sources, suitable locations for storage units can be identified.*

Energiequartier Haslach

The goal of achieving CO_2-neutral energy supplies in cities by 2050 requires new instruments to define this process. As part of the "Energiequartier Haslach" pilot project initiated by the City of Freiburg, Fraunhofer ISE is applying new tools to plan integrated energy systems. An important component is the identification of cost-optimised renovation concepts and appropriately adapted energy supply systems. In the investigated neighbourhood of Haslach, building categories appropriate to the suburb were developed which take account of the current state of renovation. Based on this, concrete, economically feasible packages of measures were developed, which are applied in energy consultancy for the suburb. The development is based on a target scenario, which represents a cost-optimised energy supply system under the local boundary conditions of the neighbourhood. The "KomMod" simulation model used for the calculations takes account of both local differences in zones and the availability of individual energy sources over time (Fig. 2). On the basis of the building classification, scenarios to develop the energy demand were calculated and models prepared for load schedules. Account is taken of the locally available potential for geothermal, photovoltaic and solar thermal renewable energy resources, and aspects which are important for the economic viability of a network-based energy supply such as district heating, e.g. heating density. The calculations can serve as a basis for decisions concerning further development of the municipal energy supply system and for creating suitable incentives.

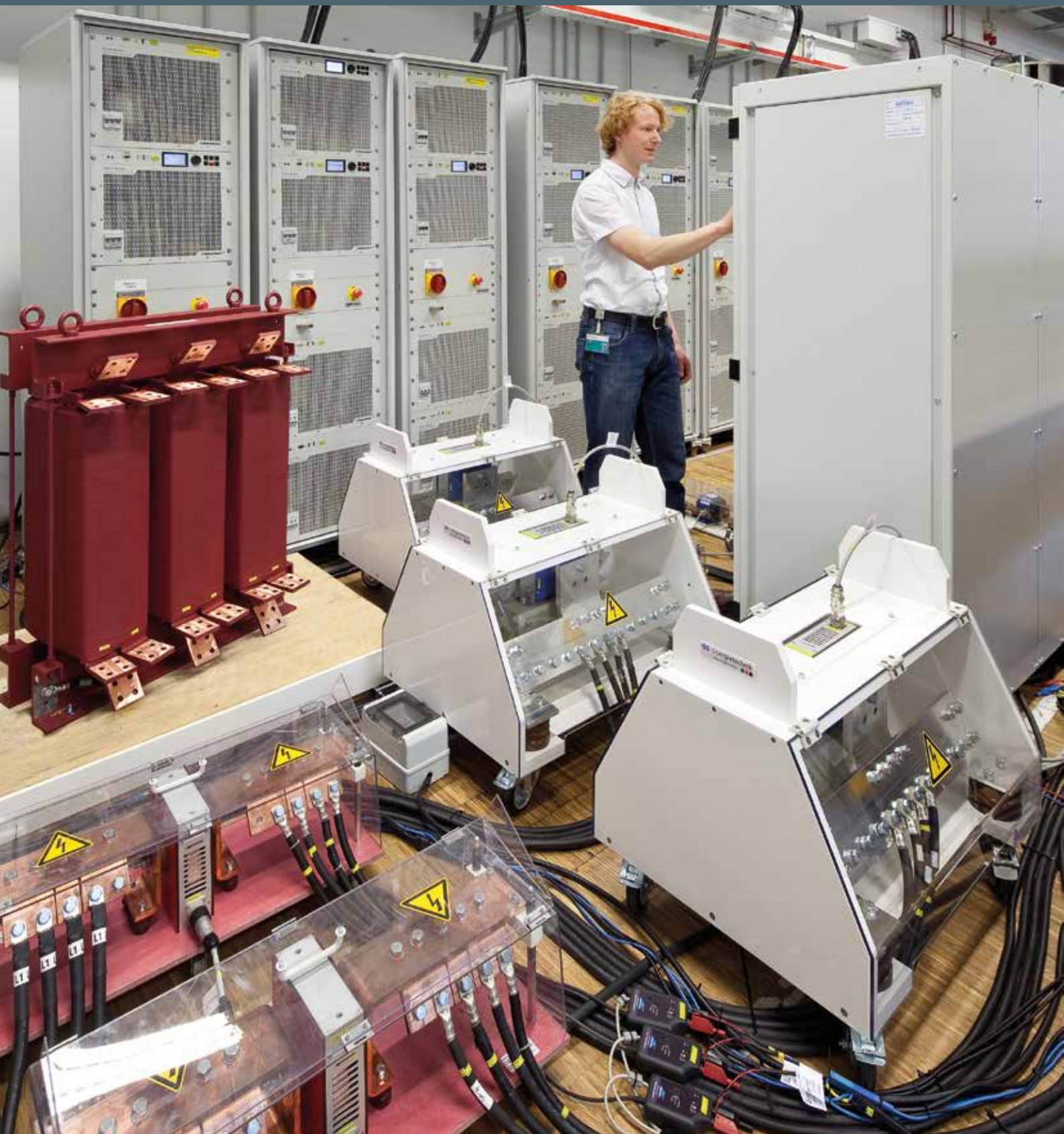
The project is funded by the City of Freiburg.

www.freiburg.de/energiequartier-haslach



3 *"KomMod" model for municipal energy systems.*

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 become feasible.

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 all applications in the power range from less than 100 watts up to the megawatt category. It has been the internationally leading research and development partner for industry in this area for decades and can now draw on many patented circuit designs. For example, the HERIC® topology developed at Fraunhofer ISE combined with the most modern electronic components meant that inverter efficiency values exceeding 99% could be achieved for the first time several years ago.

Furthermore, the future expansion of photovoltaics demands clear cost reductions also in components such as inverters. New solutions to this problem are also being prepared at Fraunhofer ISE. 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.

Components developed at Fraunhofer ISE are also used in other industrial branches such as vehicle technology or aviation. Often, concepts or solutions which were originally developed for photovoltaics can be transferred to these application areas. For example, engineers from Fraunhofer ISE 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 a broad palette of cable-connected charging systems, Fraunhofer ISE is also working on inductive high-power charging systems with rated power of more than 20 kilowatts. This can be used to meet the anticipated requirements on wireless charging of electric vehicles and provision of grid stabilisation 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, Fraunhofer ISE also conducts the low-voltage ride-through test to investigate grid voltage drops in the medium-voltage grid, which is possible in only a few laboratories. Fraunhofer ISE also contributes with its extensive experience to international standardisation work.

FURTHER INFORMATION

Staff	49
Staff: Full-time equivalent	41
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www.ise.fraunhofer.de/en/publications/50

The Inverter Laboratory of Fraunhofer ISE is equipped with all the facilities needed to test central inverters up to a power rating of 1 MW according to diverse grid feed-in guidelines.

CONTACTS

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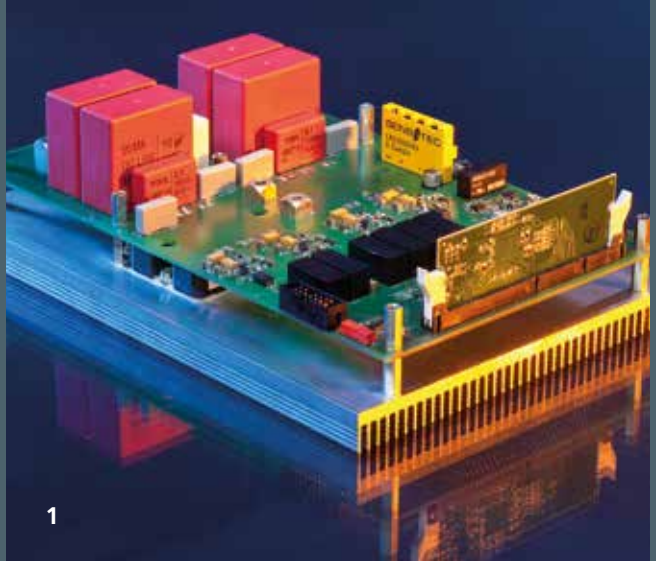
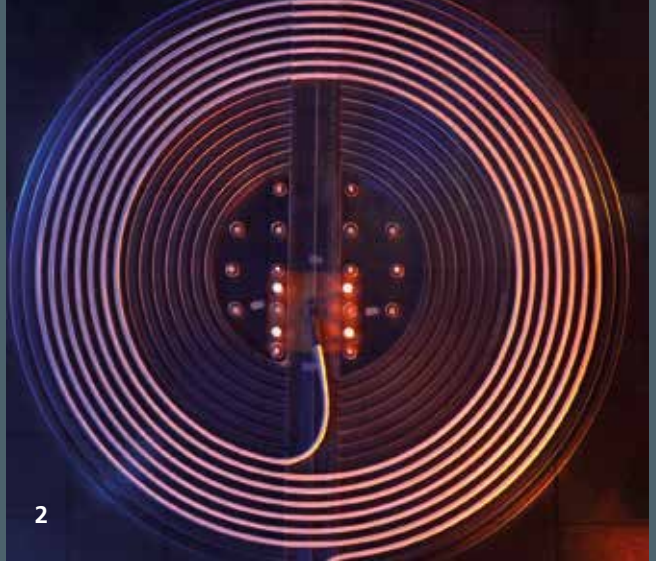




HIGHLY EFFICIENT INDUCTIVE ENERGY TRANSMISSION FOR ELECTRIC VEHICLES

Wireless energy transmission has become established in many technological applications. This type of energy transfer is considered to be promising not only for charging small devices such as electric toothbrushes and mobile phones but also for electromobility. Fraunhofer ISE is conducting research on inductive energy transmission within the "GeMo" project on community electromobility. The required power-electronic converters, the coil system and controls technology are being developed at Fraunhofer ISE. The efficiency and the power range were significantly improved by the application of new power transistors based on silicon carbide (SiC).

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

Wireless inductive energy transmission can be compared to the principle of a transformer. In both cases, an alternating magnetic field is created by a primary coil, which induces a voltage in a secondary coil. However, in contrast to a transformer, the magnetic field is not guided completely through an iron core; instead, the field must span a large air gap between the primary and secondary coils. For this reason, the main magnetic flux penetrates the secondary coil only partially and a large leakage flux arises.

In inductive energy transmission to charge an electric vehicle, the stationary coil is embedded in the road or the parking spot, whereas the second, mobile coil is integrated into the chassis of the vehicle. A cable connection between the charging station and the electric vehicle is no longer needed. The system is conceived such that energy transmission from the vehicle battery back into the electricity grid is also possible.

1 *Resonant power-electronic converter to control the stationary coil in an inductive energy transmission system.*

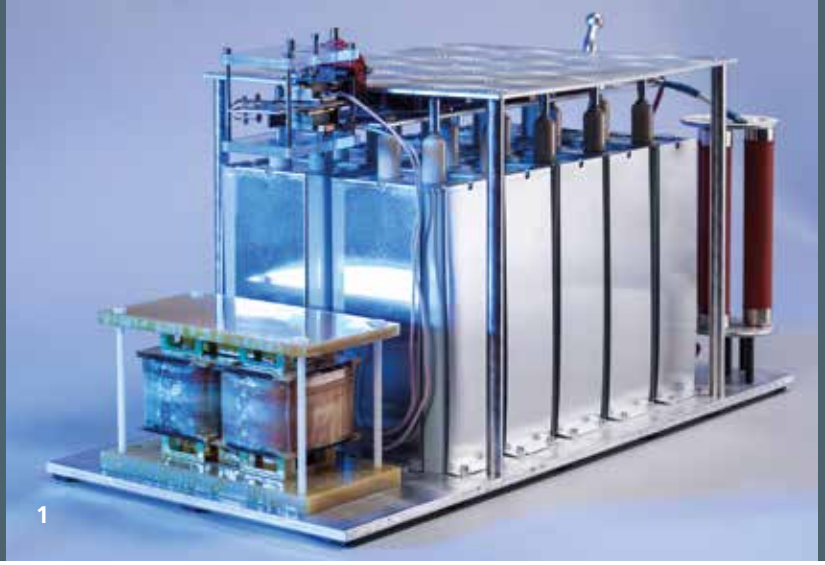
2 *Prototype of a coil (Ø app. 70 cm) for wireless energy transmission between a stationary charging station and an electric vehicle.*

This means that electricity from renewable energy sources can be temporarily stored in the vehicle battery and grid services such as the provision of operating reserve can be offered.

A particular challenge for inductive energy transmission for electric vehicles is to achieve high efficiency. The efficiency of various power electronic converters in the complete charging system can be increased appreciably by the use of new semiconductor components of silicon carbide (SiC). The low switching losses of the SiC transistors allow a high switching frequency, resulting in a mechanical configuration which is more compact and lighter than conventional devices. Further losses can be minimised by optimising the coils and the resonant circuit. The reactive power demand of the coils and their leakage field is compensated by special capacitors on the stationary and the mobile sides. Also, no reactive power needs to be exchanged between the power electronics and the coils.

The prototype of an inductive energy transmission system developed at Fraunhofer ISE has proven to be very efficient. It achieved an efficiency of 97.4% for the inductive transmission with a coil separation of 13 cm. Power up to 22 kW can be transmitted.

www.gemo.fraunhofer.de



HIGH-EFFICIENCY POWER ELECTRONICS FOR MEDIUM-VOLTAGE APPLICATIONS

Power electronics is becoming increasingly important for the electricity distribution network. The number of power converters in the chain between the generator and the consumer is rising, particularly due to the expansion of renewable electricity generation, such as photovoltaics and wind energy. The application of high-voltage semiconductor components of silicon carbide (SiC) makes it feasible to connect efficient power electronic systems directly to the medium-voltage grid. Increasing the voltage level of the converters reduces the currents on the one hand and on the other hand, the connection via an additional 50 Hz transformer can be omitted.

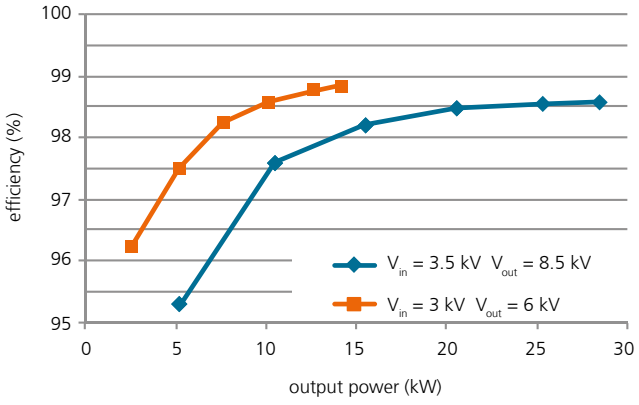
Bruno Burger, David Chilachava, Dirk Kranzer, **Jürgen Thoma**, Günther Ebert

1 *Test bench to determine the switching energy of medium-voltage transistors.*

2 *Laboratory prototype of the newly developed step-up converter with 10 kV SiC transistors.*

The band gap of silicon carbide (SiC) is about three times greater than that of silicon. As a result, SiC components have a very high breakdown field strength, which means that power semiconductor components can be manufactured with significantly higher reverse voltage for the same chip thickness. This type of component is thus predestined for use in power converters in medium-voltage applications. New power electronic solutions for the systems technology of future power supply and transmission are being developed with the first available semiconductor prototypes.

Novel 10 kV SiC MOSFETs and internally antiparallel connected SiC JBS diodes, each with a rated current of 10 A, are used. A test bench to characterise the MOSFETs was developed, with which the switching energy of medium-voltage transistors can be determined.



3 *First measurements show a maximum efficiency value of 98.5% for the rated power of 28 kW. Still higher efficiency is achieved for a lower output voltage and a lower duty cycle.*

A step-up converter was developed as a power converter which can boost an input DC voltage of 3.5 kV to an output voltage of 8.5 kV. The low switching energy of SiC MOSFETs enables a very high switching frequency of 8 kHz, which corresponds to about 10 times the value for conventional medium-voltage converters with silicon semiconductors. The higher the switching frequency, the smaller the passive components can be dimensioned, which reduces material consumption, volume and costs.

The project was funded within an internal programme of the Fraunhofer Gesellschaft, "Märkte von Übermorgen" (Markets of Tomorrow), and should be a foundation for further developments with high-voltage SiC transistors.

HOW DO INVERTERS REACT TO FAULTS IN THE ELECTRICITY GRID?

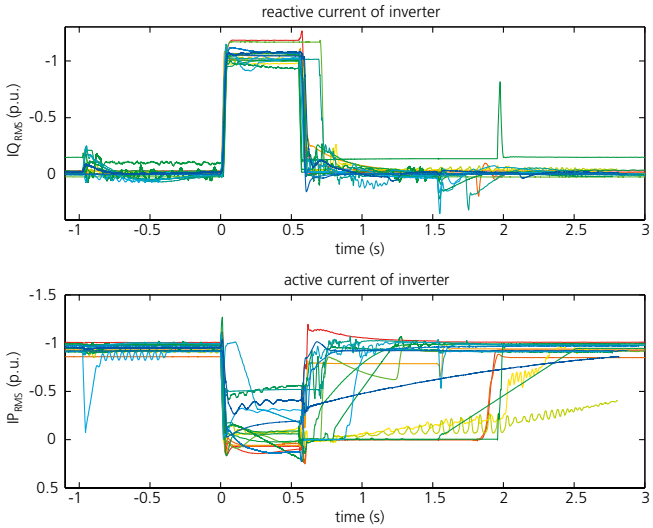
The reaction of inverters to voltage drops is investigated in the "Low-Voltage Ride-Through" test (LVRT). These inverters are controlled to stabilise the grid voltage dynamically. As the generators in conventional power plants are successively replaced, also inverters must feed in short circuit currents. The probability of a blackout is minimised by feeding in reactive current in critical states. Further, regional spreading of the grid fault is reduced, increasing the supply quality for consumers. Without grid stabilisation, protective devices in the electricity grid could not react correctly.

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

The LVRT performance of numerous inverters has been investigated in the Megawatt Laboratory of Fraunhofer ISE. Patterns can be recognised in the reaction of the test objects. For example, inverters from an earlier stage of development often use pulse blocking to prevent overcurrents when the fault begins. As a result, they cannot feed in current continuously and often inject the required reactive current more slowly. After the fault has ended, the grid voltage is strongly disturbed due to the inrush currents from the feed-in transformer. Many test objects thus increase their power only very slowly after the fault. Here and for the more frequent two-phase faults, the grid codes do not contain the necessary measures for supply reliability but only minimal requirements.

To complement the laboratory tests of single inverters, the behaviour of large solar parks during grid faults is investigated in field tests. In the interactions between the inverters and the grid equipment (medium-voltage cables and transformers) and the grid connection point, unexpected resonances can occur. They can cause switch-off and place high demands on the inverter controls. Further, the field tests provide valuable indications on the behaviour of inverters in weak, generally rural grids and the superposition of harmonics. These data, which are needed for better grid integration, are recorded very accurately with a GPS-synchronised measurement system. They also serve to validate and refine the laboratory tests.

1 *Field test with the LVRT test container in the 5 MW test field in Dürbheim to investigate dynamic grid stabilisation.*



2 *Comparison of the active current (below) and the reactive current (above) fed in by various inverters during a three-phase voltage drop to 25% residual voltage (t = 0–0.5 s). The inverters show very similar behaviour with respect to the reactive current. It is problematic that the inverters increase the active current only slowly after correction of the fault.*

ZERO-EMISSION MOBILITY

The resolution of the German Federal Government on energy transformation pays particular attention to the transport sector, and significant research funding for electromobility was authorised. This encompasses all vehicles with electric motors, regardless of whether the drive energy is drawn from a battery, a fuel cell or a battery combined with a combustion engine to increase the driving range.

In our activities in the area of zero-emission mobility, we offer research services to provide both the drive energy and the necessary infrastructure. Our research encompasses:

- battery systems and battery management
- charging infrastructure and grid connection
- fuel cells
- hydrogen infrastructure
- power electronics
- catalysts for exhaust gas treatment
- emission reduction within innovative combustion engines
- heat management
- production technology
- concept and user acceptance studies

Concerning traction batteries, we develop modules and systems for lithium technology with the necessary safety concepts and battery management systems. The thermal, electrical and electrochemical 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. The vehicle batteries must be integrated into the Smart Grid in a way which takes account of the increasing demands on 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 analyses and simulations of grid issues.

Fuel-cell vehicles offer zero-emission mobility with a wide driving range and short refuelling times. We support their development by characterising single cells, cell stacks and systems. In addition, we test peripheral and cell components under extreme climatic conditions and with respect to the 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 the hydrogen filling station as a research platform for urban mobility, component tests and holistic energy concepts.

We prepare studies on the development of hydrogen infrastructure and develop innovative technology for membrane electrolysis. Test stands for cell stacks up to 1 MW_{el} are available for this research.

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.

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

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 spectrum ranges from the development of new materials to store heat and cooling power, through their system integration, to heat management in vehicles.

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	38
Staff: Full-time equivalent	32
Journal articles and contributions to books	9
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Test drive with one of two Fraunhofer ISE fuel cell vehicles.

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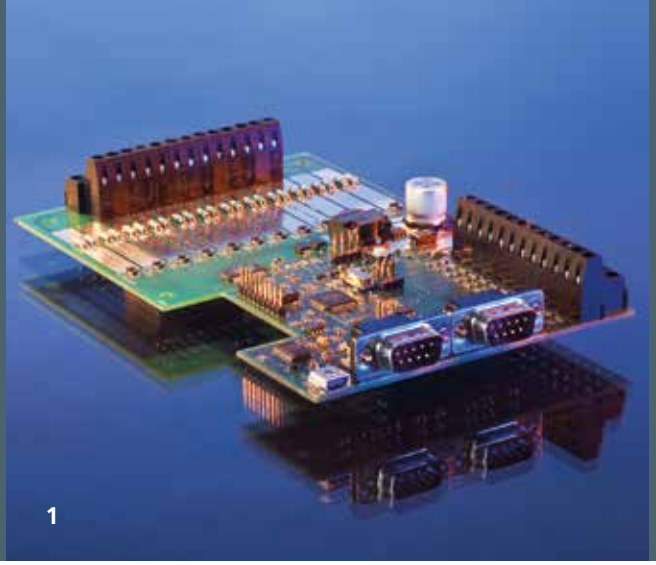
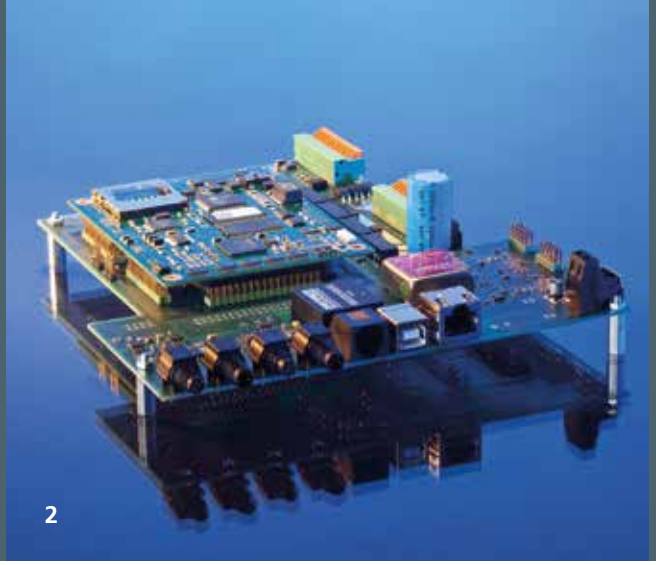




DEVELOPMENT OF INNOVATIVE BATTERY MANAGEMENT SYSTEMS

The future commercial success of electric vehicles depends decisively on the performance and quality of the batteries used on board. In addition to conception, selection of cells, mechanical configuration and electric circuit design, the central task is to develop the battery management system as the "brain" of the battery system. It is responsible for the safety functions and determining the state of charge, and is thus essential to reliable and range-optimised operation of the vehicle.

Adrian Heuer, Nikolaus Lang, **Stephan Lux**, Peter Raab, Matthias Vetter, Günther Ebert

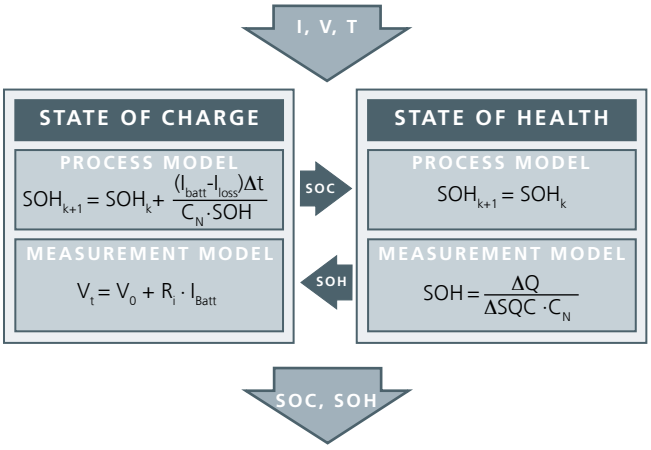
Battery management systems for monitoring and control represent the central intelligence of battery systems. They prevent both overcharging and deep discharging of a battery system and its battery cells. Extremely accurate voltage measurement of each battery cell, together with accurate measurement of the current, is the basis for correctly determining the state of charge and state of health of a battery system and its battery cells. We are developing stochastic filter procedures (or so-called particle filters) which allow the state of charge (SOC) and state of health (SOH) for every single cell to be determined during operation with great accuracy (Fig. 3). For larger systems, a sensible configuration consists of one battery management system (BMS, Fig. 1) per battery module and one higher-level, central battery management system (C-BMS, Fig. 2).

The algorithms are based on battery models, which are parameterised and validated by measurements in the battery laboratory. Beyond that, they are used for correct cell balancing. Cell balancing ensures compensation of the individual cell charge on the basis of extremely accurate SOC determination. Apart from monitoring the battery, the battery management must also be able to communicate with external control devices, provide relevant battery parameters and define target values.

As part of the internal Fraunhofer systems research on electromobility, Fraunhofer ISE is developing an innovative battery management system for a lightweight energy pack, which ensures safe and range-optimised operation by applying the features described above.

1 *Battery management system (BMS) for a battery module.*

2 *Central battery management system (C-BMS) for a battery system.*



3 *Structure of the so-called particle filter for extremely accurate on-line determination of the state of charge and state of health of the battery.*

VEHICLE-BASED GRID MONITORING AND GRID STABILISATION

The number of electric vehicles will increase appreciably in the near future. In addition, the demand for high-power charging devices will increase as battery capacities become larger. Particularly in weaker distribution grids, the load on the grid could become critical when several vehicles are charged simultaneously. At Fraunhofer ISE, the possibilities for vehicle-based, grid-stabilising measures are being investigated. In the iZEUS project, an on-board, bidirectional charger which can supply reactive power was developed, along with a vehicle-integrated control device for accurate measurement of the prevailing state of the grid. Different control strategies are being investigated and evaluated.

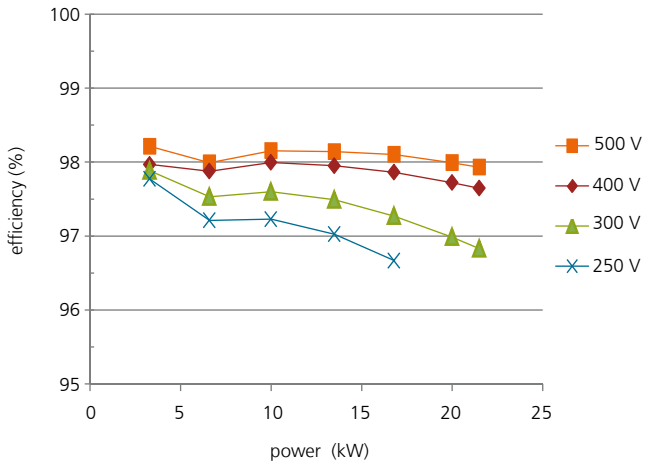
Jan Clement, Kilian Dallmer-Zerbe, Benriah Goeldi, **Robert Kohrs**, Michael Mierau, **Stefan Reichert**, Stefan Schönberger, Günther Ebert

1 *Conductive charger with water cooling. The charger is ready for installation in a vehicle.*

Intelligent grid integration of electric vehicles, e.g. controlling the charging processes with flexible tariffs, is worthwhile and important for many reasons: to adapt charging processes to the availability of renewable energy, to avoid power peaks or to extend the battery lifetime. The critical grid situations that occur will be limited in time and location. Direct control in the vehicle thus offers advantages. Possible systems and control concepts are being investigated with model-based grid simulations in a comprehensive study.

The charger developed at Fraunhofer ISE is able to exchange active and reactive power with the grid. The circuit topology is able to draw active power from the grid and to feed it back into the grid. In addition, both inductive and capacitive reactive power can be exchanged with the grid. In this way, very diverse system services such as frequency and voltage stabilisation can be offered.

Due to the circuit topology without a transformer and the application of new semiconductor components of silicon carbide, the efficiency was increased up to 98% (Fig. 2). In particular, this makes temporary storage of electricity interesting. Also, the power density was increased with respect to comparable devices. The charger and grid controller have already been taken successfully into operation in the laboratory, and can now be integrated into a vehicle (Fig. 1).



2 *Efficiency of the bidirectional charger for different battery voltages and powers.*

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

www.izeus.de

HYDROGEN INFRASTRUCTURE FOR SUSTAINABLE MOBILITY

The German mobility sector is almost exclusively dependent on conventional drive technology. By contrast, hydrogen as a fuel in fuel cell vehicles excellently complements battery-powered drive units and is thus essential to reduce emissions of greenhouse gases in the transport sector. Acknowledging this situation, the Ministry of the Environment in the State of Baden-Württemberg commissioned Fraunhofer ISE with a study which considers the status quo and the need for action concerning mobility-relevant hydrogen infrastructure, develops a road map for H_2 infrastructure up to 2030 and formulates recommendations for action based on these insights. The most important results of the "Hydrogen Infrastructure" study are presented below.

Tom Smolinka, **Christopher Voglstätter**, Christopher Hebling

Due to diverse activities such as the "Clean Energy Partnership" (CEP) and "H_2Mobility", Germany is establishing itself as the internationally leading market for hydrogen-based mobility. For example, in October 2013 the industry reaffirmed its intention to increase the number of public filling stations from 15 today to 100 in 2017 and 400 in 2023.

To establish a hydrogen infrastructure in the State of Baden-Württemberg, Germany, the market penetration of hydrogen in the transport sector was quantified, and the demand for hydrogen, the number of filling stations required and their capacity were derived for the period up to 2030. In Baden-Württemberg, up to 330 filling stations and a hydrogen turnover of 50,000 tonnes per year are expected for 2030.

1 *Solar hydrogen filling station at Fraunhofer ISE.*

2 *The 96-page study was released on 26th March, 2013 by the State of Baden-Württemberg, Ministries of the Environment, Climate Protection and the Energy Sector, of Finance and Economics, and of Transport and Infrastructure, and by e-mobil BW GmbH. It can be downloaded free of charge from e-mobil BW GmbH under: www.e-mobilbw.de*

The issues to be faced in building up a hydrogen infrastructure include the cost, reliability, approval / testing and authorisation of the filling stations, the (further) development of components and the current lack of demand for hydrogen. On this basis, four main tenets were formulated:

- Hydrogen as a fuel can make an important contribution to reaching the climate protection goals and supporting the expansion of renewable energy usage.
- To reduce the investment risk and prepare the market, public funding will continue to be needed.
- Standardisation will facilitate the establishment of H_2 filling station infrastructure.
- Further activities by the actors involved are needed to achieve commercially mature infrastructure.

STORAGE TECHNOLOGIES

The transformation of our energy system from domination by fossil fuels toward an increasing fraction of renewable energy is subject to great challenges, including the strong temporal fluctuation in availability of renewable energy sources, which cannot be controlled and can be predicted only to a limited degree. As a result, energy storage assumes a central role: A stable energy supply with renewable energy will become feasible only if efficient and cost-effective forms of energy storage can be developed. In doing so, it is essential to take the complete energy supply chain into account and to decide on 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 technologies:

- 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 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 analyses. We develop intelligent charging and operation management strategies which can be easily integrated into microcontrollers for charge controllers, equipment controls and battery management systems. We apply simulation-supported analysis and dimensioning when developing stacks, systems and battery management systems for redox-flow batteries.

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 as a core element for chemical storage in combination with renewable energy. Our work is currently focussing on lifetime analysis and the optimisation 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. The development of accelerated aging tests on 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 optimise such storage units as individual components and within systems. The goal is to increase energy efficiency and reduce costs.

If 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 +300 °C. Simulations serve here to optimise 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 optimise storage concepts, which are designed for temperatures from 200 °C to 600 °C.

WEITERE INFORMATIONEN

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The four oxidation states of the diluted vanadium electrolyte (from left to right: V^{5+}, V^{2+}, V^{4+}, V^{3+}).

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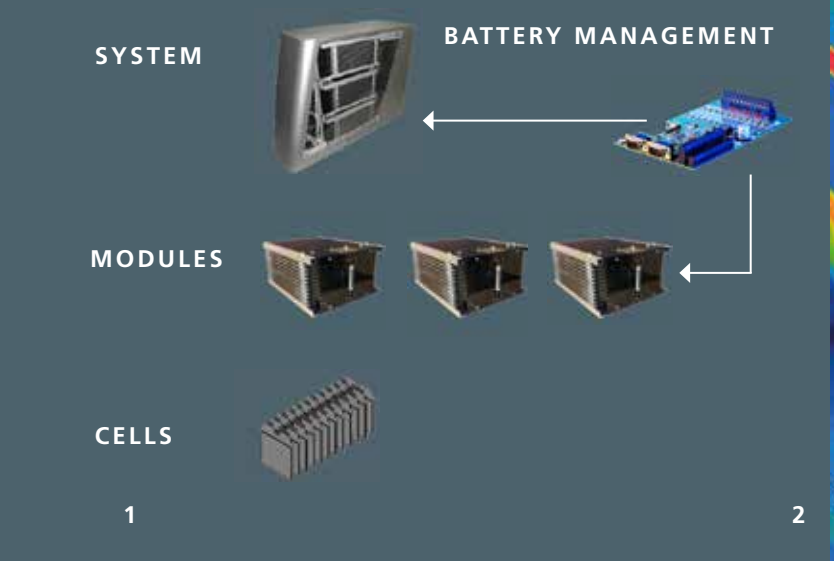
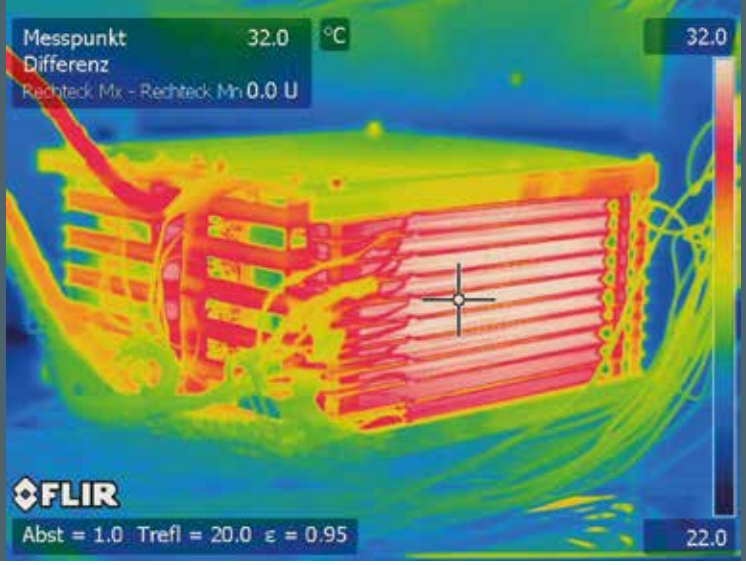




DOMESTIC BATTERIES FOR INTERMEDIATE STORAGE OF PV ELECTRICITY

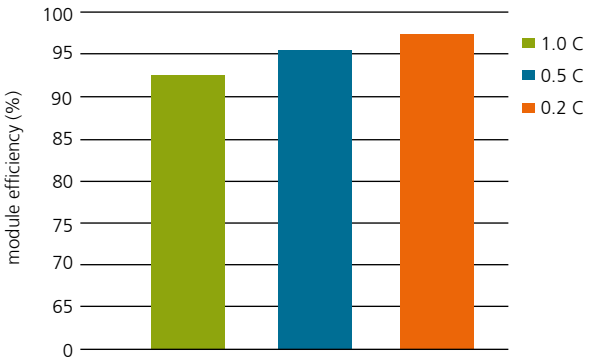
Decentralised battery systems for intermediate storage of PV electricity are essential to further expanding the use of renewable energy. Integrated into buildings, these storage solutions must be highly efficient, safe, reliable and durable. In addition, they must be easy to combine with existing and future PV system installations. In order to meet these requirements, we are developing innovative battery systems based on lithium-ion technology within the Fraunhofer project on "Urban Hybrid Energy Storage". The systems are distinguished particularly by their modularity, a sophisticated cooling system and intelligent battery management with accurate algorithms for state determination.

Martin Dennenmoser, Nikolaus Lang, Stephan Lux, Peter Raab, **Matthias Vetter**, Günther Ebert

Lithium-ion batteries are ideally suited for intermediate storage of PV electricity due to their specific characteristics. However, a series of complex development steps is needed to progress from single cells to a functional battery system. The cells are connected to form so-called battery modules (Fig. 1). They must be actively cooled in dependence on the operating point, be easily integrated into a battery system and be monitored by a battery management system.

In the construction of the battery modules, our main priority is to ensure that the temperature distribution is as homogeneous as possible and that the system does not need to run the integrated cooling system over a wide operating range (Fig. 2), but without causing premature aging of the cells or inducing states critical to safety. With this approach, the peripheral losses – e.g. due to the ventilator – can be reduced and thus the system efficiency raised and the lifetime lengthened.

1 *Design of a modular lithium-ion battery system for intermediate storage of PV electricity. The individual battery cells are connected in series to form modules and are then integrated into a battery system together with the central battery management unit, which forms the interface to peripheral components such as the inverter.*
2 *Thermographic image of the lithium-ion battery module during the discharging phase with a C-rate of 1 (discharge in one hour) without activated cooling. After 18 minutes, the temperature at the hottest point has risen only to 32 °C.*



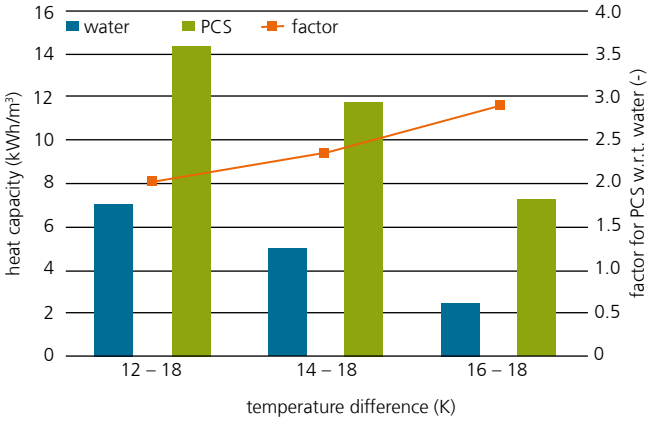
3 *Efficiency values of the lithium-ion battery module for different C-rates (charging and discharging in one hour, two hours and five hours respectively).*

The battery management is designed such that several modules are monitored and controlled by one unit. A separate circuit board for each module is planned only for so-called cell balancing, which is intelligently integrated into the flow channel of the ventilation unit. This reduces the amount of hardware needed compared to systems with integrated module management. As a result, costs can be reduced at the system level.

PHASE CHANGE SLURRIES TO STORE COOLING POWER IN HEAT PUMP SYSTEMS

Phase change slurries (PCS) consist of a phase-change material (PCM) dispersed in water. They offer significantly higher storage density for small temperature differences than for water alone. They are thus particularly suitable for compact storage of cooling power to cool buildings and technical systems. They also allow storage to be integrated in locations where there is insufficient space for conventional cold storage units. In systems with compression chillers, the generation of cooling power can be separated from the cooling demand. Such systems can then be controlled according to user demand and react flexibly to requirements of the electricity grid.

Stefan Gschwander, Jan Rudolph, Peter Schossig, Laura Vorbeck, Hans-Martin Henning



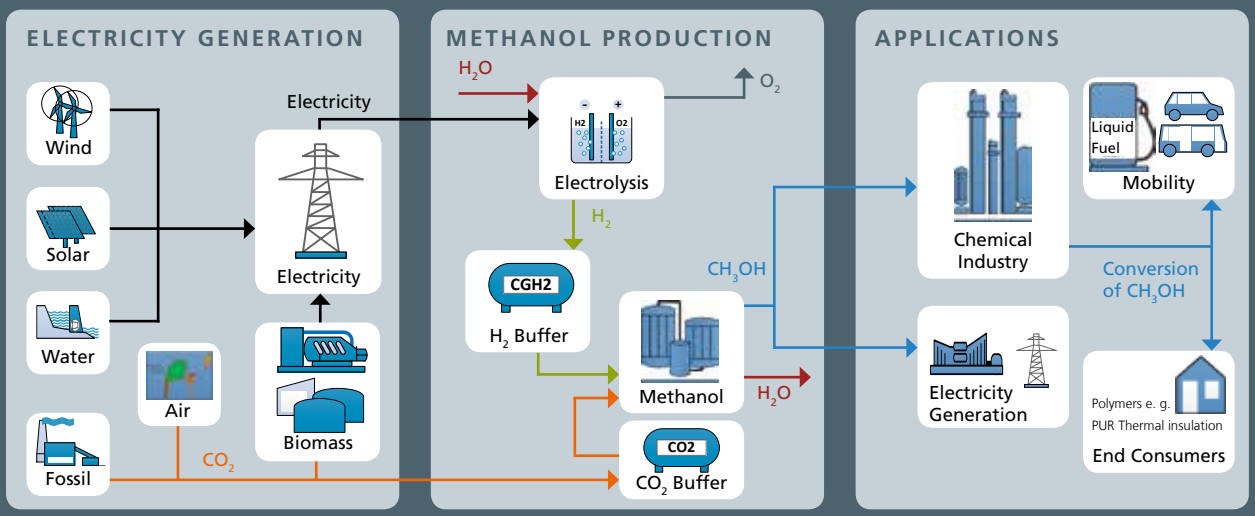
3 *The PCS offers a significantly higher storage density than water. This means that storage units can be dimensioned smaller for the same heat capacity. The smaller the usable temperature difference, the greater is the advantage of PCS compared to water.*

1+2 *The PCS used is a dispersion of PCM and water. It remains liquid, independent of the state of the PCM, and can be pumped like any other liquid through a hydraulic network.*

In the "MESSIB" project (Multi Energy Storage Systems in Buildings), we have developed PCS with a melting temperature between 14 and 18 °C together with BASF AG and further partners. In this temperature range, the storage density of PCS is 2.4 times greater than water. This material was used in the Solar House in Freiburg to store cooling power. The system consists of an earth probe as a heat source and sink, a reversible heat pump, a 1000 l buffer tank and cooling ceiling elements, which are supplied directly from the tank without any further intermediate loop. The PCS was cooled with the reversible heat pump via a plate heat exchanger, stored and used during the day to cool two offices. The heat pump can draw power directly from the grid or from its own PV system. This provides the option of storing the electricity generated on site in summer as cooling power, to be used at a later time.

With this system, the application of PCS as a medium to store and distribute cooling power was tested and confirmed. Low viscosity is important for energy-optimised and reliable operation, as it ensures that the energy demand to transport the medium is low and that the heat exchangers and cooling ceilings perform well. In addition, the quasi-isothermal absorption and release of heat by the PCS also has a positive effect on performance.

Our goal is to optimise PCS further in future to demonstrate the potential of these storage liquids in the building and industrial sectors. The project was supported by the European Union (EU).



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CHEMICAL STORAGE: CONVERSION OF CO_2 AND H_2 TO METHANOL

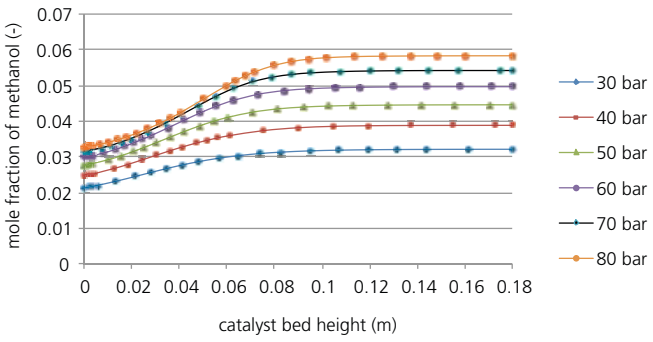
Due to the increasing proportion of electricity generated from fluctuating sources, seasonal storage is needed on a large scale. The power-to-liquid approach that we are pursuing aims to generate large quantities of hydrogen by the electrolysis of water using sustainable energy sources. The hydrogen is then converted to methanol by reaction with carbon dioxide. Liquid methanol is easy to store and transport. At Fraunhofer ISE, a very compact test rig was designed and constructed, which is aiding the process optimisation and design of an industrial system for Solvay Fluor GmbH.

Thomas Aicher, Markus Jorgas, **Achim Schaadt**, Vitalis Weiß, Christopher Hebling

Methanol is one of the most important raw materials for the chemical industry. The annual global production is about 60 million tonnes (2012). About 85% of it is used as a raw material for synthesis or as a solvent. The rest is used in the energy sector as a fuel or a fuel additive. Natural gas is currently almost the only carbon source for methanol production, although this releases large amounts of greenhouse gases. These emissions could be reduced significantly if carbon dioxide – ideally from biogenetic processes – is converted together with regeneratively produced hydrogen to form methanol, as our life cycle assessment calculations have demonstrated.

Before starting experimental tests, we carried out process simulations based on the steady-state kinetic model of Bussche and Froment to dimension and analyse our two-stage system. As methanol synthesis is an exothermal process, low temperatures are thermodynamically favourable. However, the currently used catalysts only become sufficiently active above temperatures of typically 250 °C. An important project goal is thus to use more active catalysts which are effective at lower temperatures. At present, a conventional Cu/ZnO

1 *The diagram shows the complete process chain from the generation of electricity from renewable sources through methanol production to its application in different markets. Conversion to liquid fuel is particularly interesting, as it will remain essential for some mobile applications, and offers the potential to save large amounts of CO_2.*



2 *Results of the Bussche-Froment simulation of one of the two reactors. As the methanol synthesis is based on a volume-reducing reaction, the methanol fraction increases with increasing pressure. The simulation also shows that the equilibrium concentration is already reached at a catalyst bed height of 0.1 m and that no further reaction occurs in the second half of the reactor (which could thus be dispensed with).*

catalyst is being tested at Fraunhofer ISE to take the system into operation and establish a suitable reference system.

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

DEVELOPMENT AND OPTIMISATION OF REDOX FLOW BATTERIES

To develop a scalable electricity storage unit with an electric power of 100 kW_{el} and a capacity of 1 MWh_{el}, we are working on the stack and system development and the management of redox flow batteries at Fraunhofer ISE. By applying simulation-supported analysis and design of redox flow batteries, we identify optimisation potential at the cell and stack level and use this to further develop the design. Within the "1 MWh Redox-Flow Netzspeicher" project on grid-connected storage, we have developed an optimised cell stack with a power of 5 kW_{el} for use in mini-grid systems or grid-connected storage systems. Cycling efficiency values of above 80% have been achieved at the stack level. Current research is concentrating on further increasing the power and energy density and reducing the production costs of a 5kW_{el} cell stack.

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

1 *Testing a new stack design for a 5 kW_{el} redox-flow battery with 40 cells and a cell area of 2000 cm^2. A fully automated test field system for up to 10 kW_{el} was constructed and taken into operation, and is now available for comparative and long-term measurements. In our new development centre, a test field is currently being established for investigation of cell stacks up to 35 kW_{el} as well as multi-stack configurations up to 52 kW_{el}.*

Fundamental questions for optimisation are answered at the cell level by multiphysical modelling. In this way, we gain deeper understanding of the relevant processes and loss mechanisms. Specific measurements in situ of single cells and ex situ measurements of the electrode, membrane and electrolyte enable the charging and discharging processes to be characterized and the identification of material parameters as an essential data base for modelling and simulation. A fully automated test stand with detailed test log procedures was developed for experimental work on single cells. It is available for comprehensive materials characterization.

This year, the development and test operation of a 5 kW_{el} cell stack was successfully completed. This power class is very suitable for investigating and optimising system-relevant process parameters. Based on the experience gained during this developmental work, we are optimising the stack design further and pursuing alternative cell concepts to increase the power density and reduce the production costs.

Based on the promising results of the development work at the materials, stack and system levels, a grid-connected, redox flow battery system with a power of 5kW_{el} and a capacity of 20 kWh was constructed and taken into operation. Operating data from a field test are currently being recorded and analysed.

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

ACTIVE LATENT HEAT STORAGE FOR SOLAR THERMAL POWER PLANTS

The project goal is to develop a latent heat storage unit for direct steam-generating, solar thermal power plants. The storage unit is loaded with steam generated by solar energy, so that steam is available also during periods without solar radiation. With respect to exergy, it is favourable to store the heat released during condensation in a solid / liquid phase change, as the storage process then occurs almost isothermally. A novel concept was developed to this purpose. A screw heat exchanger transports the storage medium (nitrate salt) according to the principle of an Archimedes screw and simultaneously introduces heat (melting the phase-change material) or extracts it (crystallisation). This storage system is modelled and then investigated and optimised by system simulations for a 50 MW power plant with direct steam-generating Fresnel collectors.

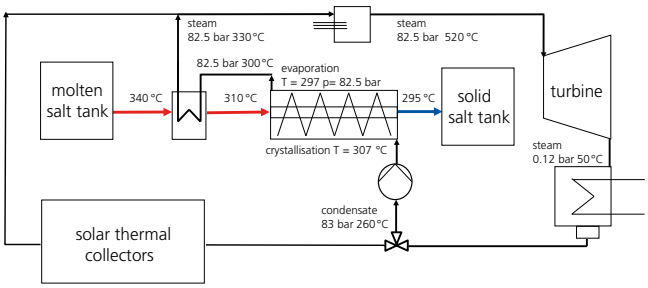
Anton Neuhäuser, **Verena Zipf**, Werner Platzer

The application of latent heat storage to a 50 MW reference power plant is being evaluated by system simulations. To do so, a model of the screw heat exchanger was prepared for "ColSim", a simulation environment developed at Fraunhofer ISE. Different system concepts (two or three storage tanks) are being defined (Figs. 3 and 4) and suitable operating concepts developed. For final evaluation, the levellised costs of electricity will be calculated from annual yield calculations and cost assumptions. To increase the economic potential, an optimisation algorithm is applied which varies system parameters (e.g. solar field dimensions, flow rates) to minimise the levellised cost of electricity.

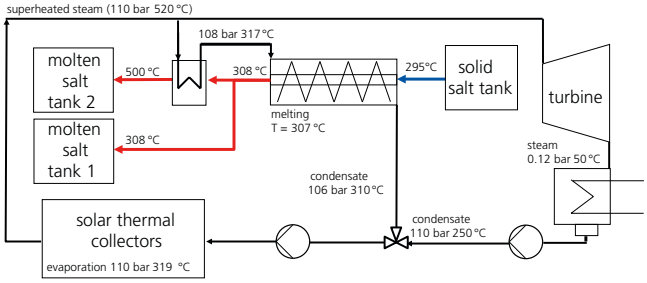
The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

1 *Test stand to investigate the novel latent storage concept: Prototype with 5 kW heating power and screw heat exchanger with two intermeshing screws.*

2 *Crystallisation of molten nitrate salt in the screw heat exchanger: The crystalline salt is directly scraped off and ground down.*



3 *Night operation of a 50 MW direct steam-generating power plant with two storage tanks and additionally installed fossil-fuelled auxiliary burner during tank discharging.*



4 *Daytime operation of a 50 MW direct steam-generating power plant with three storage tanks during tank charging.*

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. Other countries, in North Africa and Asia for example, 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 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. For example, the combination of different energy technologies or the integration of storage-coupled power plants can result in more constant electricity generation.

These changes stimulate new research questions, which mainly address the integration and interaction of renewable energy resources in the 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?

Fraunhofer ISE offers a range of approaches to address these issues, which include:

- techno-economic assessment of energy technologies
- 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 analysed at Fraunhofer ISE according to technical and economic criteria such as the levellised 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 System 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 functions between components of the energy system. In this way, our models provide a well-researched foundation for decisions on the boundary conditions for a future power supply.

Another instrument for analysing energy systems is the development of business models, which we offer 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. Fraunhofer ISE thus offers comprehensive methods and tools to meet the challenges which a transforming energy system presents.

FURTHER INFORMATION

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Renewable energy has become an important industrial sector. Its growth has contributed to pronounced changes in the energy system.

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1 *The interest in renewable energy is growing in the Middle East and North Africa (MENA).*

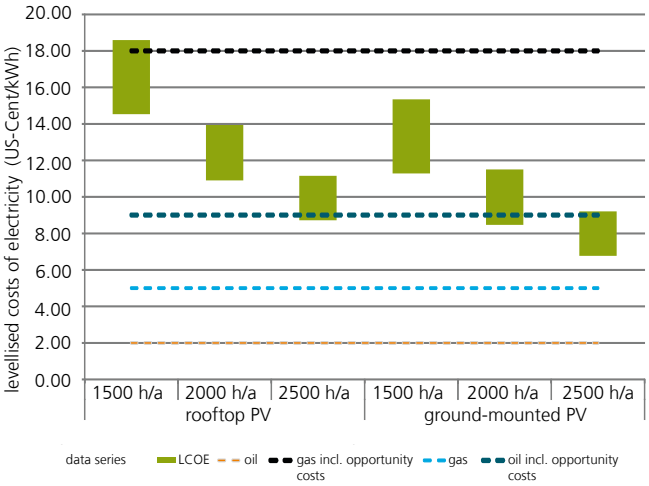
ECONOMIC FEASIBILITY OF PHOTOVOLTAICS IN THE MENA REGION

The globally increasing demand for energy is also reflected in the Middle East and North Africa (MENA). Expenditure for fossil fuels is rising, oil and gas reserves are being depleted and CO_2 emissions are increasing. To counteract these trends, many MENA countries are setting ambitious goals for the expansion of renewable energy systems. Fraunhofer ISE is supporting the evaluation of PV potential, real costs and economic feasibility. Comparisons to other technologies are made for photovoltaics with respect to costs, taking opportunity costs into account, and the resulting potential to reduce CO_2 emissions.

Niklas Hartmann, Verena Jülch, Christoph Kost, **Noha Saad Hussein**, Charlotte Senkpiel, Jessica Thomsen, Thomas Schlegl

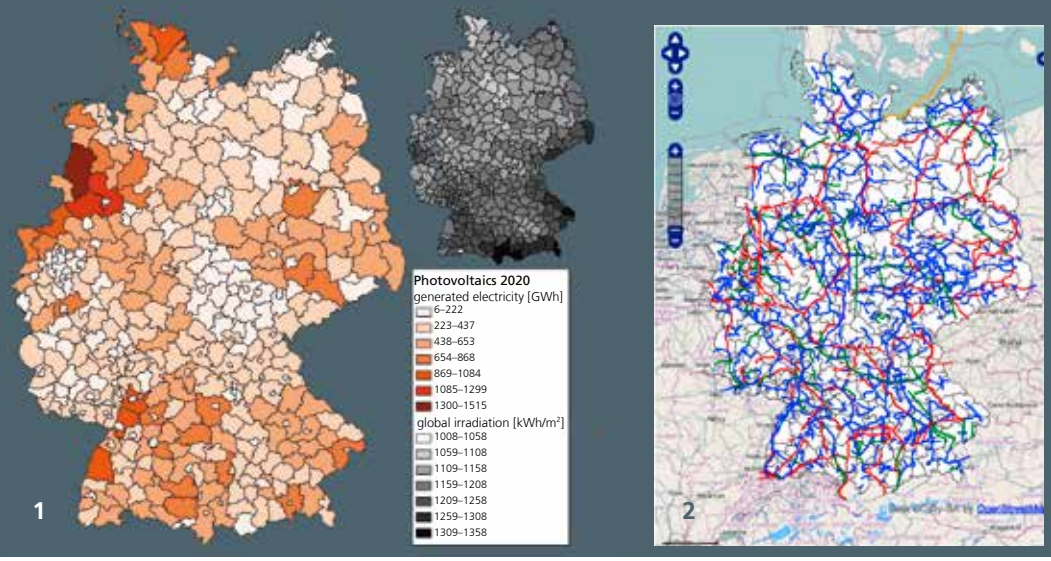
By introducing photovoltaic electricity generation, countries which depend strongly on fossil fuel imports or companies with high expenditure for energy can actively reduce the expense of meeting their energy demand. Oil- or gas-exporting countries benefit from installing photovoltaics by saving fossil fuels themselves and gaining significant profits by exporting them instead.

To evaluate the economic PV potential of these countries, initially the available technical potential for free-standing and rooftop systems is determined. However, the number of real installations depends strongly on economic factors concerning the systems at the relevant locations, which must often compete against subsidised electricity generation from fossil fuels. Thus, not only the levellised costs of electricity but also the opportunity costs for fossil fuels play a role in the economic analysis. This allows comparison between the levellised cost



2 *Comparison of the levellised cost of electricity (LCOE) for PV systems and conventional technology with opportunity costs.*

of electricity from photovoltaics under local conditions and gas and oil including opportunity costs (Fig. 2). It often becomes evident that when the opportunity costs are taken into account, photovoltaics often features lower levellised costs of electricity. In this way, the economic feasibility of PV systems, their potential for expansion and possibly necessary regulatory measures can be evaluated. A further aspect is the reduction of CO_2 emissions, which plays a great role in MENA countries. We therefore analyse the savings potential offered by the application of renewable energy.



REGIONAL MODELLING OF ENERGY DISTRIBUTION

The goal of the German Federal Government is to reduce the emission of greenhouse gases in 2050 by 80–95% compared to 1990. In addition to analysis of a cost-optimised future energy system, the question concerning the transformation rate for an energy system is also relevant. Time-resolved transformation processes thus play an important role for energy system analysis. Based on modelled development routes, the CO_2 reduction, required grid extension or necessary flexibility options can be analysed. Within the internally funded research project on "Renewable Energy Scenarios – E2S", the route to a future energy system based on renewable energy is analysed and evaluated.

Günther Ebert, Niklas Hartmann, **Niklas Kreifels, Charlotte Senkpiel**, Christof Wittwer, Thomas Schlegl

A central question in the presentation of development routes is: Which group of actors will invest in which technology at which location for a given set of boundary conditions? Based on the present German energy system, the "E2S Investment Model" exploratively determines the expansion of renewable energy technologies, conventional power plants and storages. Political, economic and technological boundary conditions are taken into account. The examined investor groups consist of private persons, utilities, banks and foundations, commercial enterprises, project developers and farmers. Each group has different technological preferences – e.g. private persons invest primarily in rooftop PV – and different financing conditions. As a result, the investment in a technology is not equally beneficial for every investor. In addition, the location plays an important role particularly for renewable energy technologies due to their dependence on natural resources. The "E2S investment model" also takes account of the existing residential building stock with respect to renovation and the form of heating energy.

1 *Predicted photovoltaic electricity generation for 2020, spatially resolved according to urban and rural administrative districts. The black and white map of Germany illustrates the solar radiation distribution on which the calculations were based.*

2 *Data extracted from OpenStreetMap to model the transmission grid. This was the basis for simulating the load flow in the grid.*

The "E2S full-year simulation model" simulates the operation of a given energy supply structure throughout a year and the associated regionally and temporally resolved electricity and heat flows. It consists of individual sub-models, which include models to simulate the electricity generation of PV and wind energy systems based on meteorological data, the operation planning of large power plants and storage units, decentralised cogenerating units and the thermal demand. Further, a grid model is integrated which includes all power lines from the 110 kV to 380 kV levels and simulates the load flow.

As an example, Fig. 1 describes the simulated annual electricity yield from the fluctuating photovoltaic technology for 2020, spatially resolved according to urban and rural administrative districts. This was based on results for the installed power which were determined by the "E2S investment model". Private investors, with a share of more than 60%, represent the largest financing group for PV systems. Bavaria, North Rhine-Westphalia and Lower Saxony are the States with the largest quantities of installed PV power. Fig. 2 presents the data extracted from OpenStreetMap on power lines. This was used to model the transmission grid, allowing the load flow to be simulated, and the degree of capacity utilisation and overloading to be determined.

INTEGRATED HEATING AND COOLING STRATEGY FOR GERMANY

Around 57% of the end energy demand in Germany is used as heat, of which a good half is for space heating, and slightly less than 40% and 10% are for process heat and domestic hot water respectively. Around 15% of the German electricity demand is used for cooling processes, mainly in the industrial sector. Thus, heating and cooling applications are decisive contributors to the emissions of greenhouse gases related to energy consumption. The central questions of our analysis are therefore: Which combination of reduced consumption, increased efficiency in conversion chains and application of renewable energy is recommended to reach the goals set for heating and cooling applications concerning climate protection? And which package of political measures will yield the envisaged results?

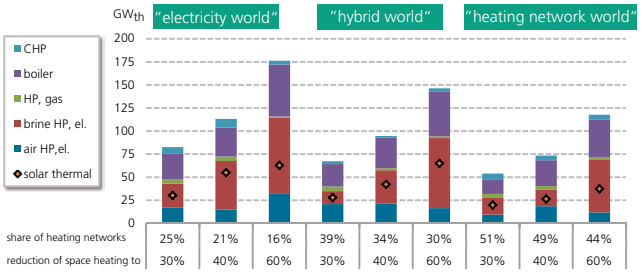
Sebastian Herkel, Christoph Kost, Andreas Palzer, Matthias Schicktanz, Lena Schnabel, **Hans-Martin Henning**

A project consortium led by Fraunhofer ISE was commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) to carry out a comprehensive analysis of the German heating and cooling sector. In the first phase, scenario analyses were prepared up to 2020 for all consumption sectors – households, commerce, trade, services and industry – based on very comprehensive modelling. The reports showed that the goal of meeting a share of 14% of the end energy demand for all heating and cooling applications by renewable energy can be achieved only by a combination of different, ambitious measures, including legal changes, financial support and specific instruments and information for each target group.

In a second phase, an outlook on the heat demand of the building sector was prepared for the period up to 2050. To this purpose, consistent target systems were defined, which

1 *Use of solar thermal process heat in a commercial laundry.*

2 *Solar hydrogen filling station at Fraunhofer ISE.*



3 *Composition of the installed power in GW for heating technology in individual buildings resulting from optimisation calculations for different target systems with a specified degree of energy renovation and installation of heating networks. The lower row of values along the abscissa represents the predicted space heating demand in the building sector for 2050 as a percentage of the value for 2010. The upper row specifies the share of space heating which is met by heating networks. (CHP = combined heat and power, HP = heat pump)*

agree with the climate-protection goals of the German Federal Government. In this work, calculations and optimisation were also made with the "REMod-D" (Regenerative Energy Model for Germany) model, which was developed at Fraunhofer ISE. Among other aspects, the results underlined the great importance of heat pumps for future heating technology (Fig. 3).

Our project partners were the Fraunhofer Institute for Systems and Innovation Research ISI, Öko-Institut, Bremer Energie-Institut, Energy Economics Group of the TU of Vienna and IREES GmbH - Institut für Ressourceneffizienz und Energiestrategien.

www.ise.fraunhofer.de/remod-d

FIELDS OF EXPERTISE

Macroscopic image of a heat exchanger structure of metal wire mesh for efficient evaporation of natural refrigerants. The prototype has a width of app. 400 mm and a height of app. 100 mm.

The Fraunhofer Institute for Solar Energy Systems ISE conducts research and develops technology for an environmentally friendly energy supply. The work focusses not only on solar energy conversion but also flexible storage, intelligent distribution and efficient utilisation of energy. Like all Institutes of the Fraunhofer-Gesellschaft – the largest organisation for applied research in Europe – Fraunhofer ISE pursues an approach with a strong practical orientation. The aim is to bring new products and processes to commercially marketable maturity with and for industrial partners. The broad, applications-oriented spectrum is reflected in the twelve areas of business of Fraunhofer ISE: Energy-Efficient Buildings; Silicon Photovoltaics; III-V and Concentrator Photovoltaics; Dye, Organic and Novel Solar Cells; Photovoltaic Modules and Power Plants; Solar Thermal Technology; Hydrogen and Fuel Cell Technology; System Integration and Grids – Electricity, Heat, Gas; Energy-Efficient Power Electronics; Zero-Emission Mobility; Storage Technology; Energy System Analysis.

In order to work on this extensive field of research, different scientific qualifications and methods are needed. The 1300 employees of Fraunhofer ISE thus include specialists from different disciplines who cooperate in interdisciplinary research. Work on the twelve business areas listed above benefits particularly from knowledge, scientific approaches and methods from the following eleven fields of expertise:

- Materials Research
- Semiconductor Technology
- Surface Technology
- Optics and Photonics
- Systems Technology
- Electrical Engineering and Controls Technology
- Information and Communications Technology
- Chemical Engineering and Process Technology
- Production Technology
- Measuring, Testing, Monitoring
- Modelling and Simulation

The Institute cooperates closely with universities, technical colleges and other research institutions so that the research for partners and clients from the industry or the public sector always benefits from up-to-date research results and methods. Researchers from Fraunhofer ISE are involved in academic teaching (page 153). Numerous graduate and undergraduate students from different disciplines contribute with their knowledge and enthusiasm to further expertise at the Institute (page 150). In addition, Fraunhofer ISE organises specialist congresses and conferences, thus encouraging the dissemination of knowledge. Staff members of Fraunhofer ISE regularly receive prizes and awards for their research work (page 14).

High-quality facilities, instruments and laboratory equipment enable the researchers to further develop scientific procedures and methods in the eleven fields of expertise. One example for this is the new building with a laboratory area of 2400 m^2 in Freiburg, which was officially opened in 2013. Scientists work there on coatings, microstructures and optical and photonic applications for solar thermal technology and photovoltaics. The specific construction and equipment of the laboratories particularly support the further growth of expertise in the fields of optics and photonics, materials research and surface technology (page 132/133). Competence and knowledge from the Institute are thus increasingly demanded also by clients from other sectors than solar energy.

Within the field of expertise on Measuring, Testing and Monitoring, a centre for heat transformation is being newly planned at Fraunhofer ISE. Driven by different forms of energy, heat transformation processes offer numerous alternatives to provide heat at specific temperatures for different purposes. The Institute possesses expertise on various forms of input energy (such as electricity, heat, fuels) and target temperatures (for heating and cooling), and can provide knowledge on materials research through component development up to systems evaluation and optimisation (page 130/131).

Further information on the eleven fields of expertise:
www.ise.fraunhofer.de/en/fields-of-expertise

1

2

HEAT TRANSFORMATION

FIELDS OF EXPERTISE
MATERIALS RESEARCH
MEASURING, TESTING, MONITORING

Heat transformation processes enable heat to be raised from a lower to a higher temperature level. Different forms of energy (electricity, fuels, heat at a higher temperature level) are used as the driving energy. Heat pumps are the best known application of heat transformation for providing heat in buildings; they enable useful heat to be provided by the application of ambient heat (outdoor air, ground). The generation of cooling power is fundamentally based on heat transformation processes. Fraunhofer ISE has been working intensely in this area on topics ranging from materials and component development up to system evaluation and optimisation. We now have a new, high-performance testing and development centre for a broad spectrum of technologies, application areas (heating, cooling) and power classes.

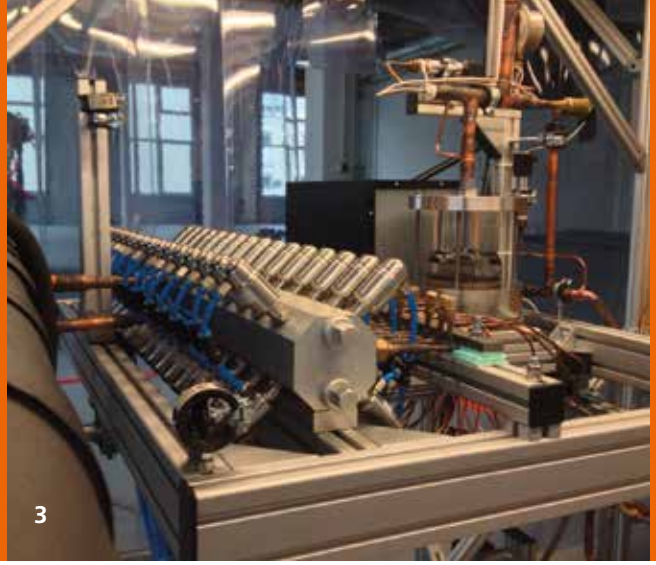
Constanze Bongs, Danny Günther, Stefan Henninger, Ivan Malenković, Marek Miara, Alexander Morgenstern, Björn Nienborg, Thore Oltersdorf, Lena Schnabel, **Peter Schossig**, York Tiedtke, Jeanette Wapler, Hans-Martin Henning

Around 50% of the German end energy consumption is used to provide heating and cooling. Processes in these sectors thus offer great potential for energy-efficient solutions and the application of ambient energy or the utilisation of renewable energy sources.

Fraunhofer ISE has conducted extensive **field tests of heat pump systems** over many years, both for residential and non-residential buildings representing new buildings and the existing building stock. These investigations enable not only reliable determination of coefficients of performance but also detailed analysis of system behaviour. Typical faults in practical operation can be identified and recommendations for improvement prepared, which range from the planning phase through installation and commissioning to the operation phase. Our work documented the technical status which has been achieved, reliably and with great practical relevance. The standardised measurement and analysis procedures developed here are defining international benchmarks and can also be transferred to other application areas.

Our work in **component development** for vapour compression is concentrating on systems requiring minimised amounts of refrigerants, systems to avoid incorrect distribution of air or the refrigerant and technology to improve the safety of systems employing flammable refrigerants. **Test stands** are available for fluid distributors, air-cooled evaporators and multi-fluid evaporators for almost all conceivable types of heat pumps and cooling systems (useful power of up to 50 kW; all source and sink media).

In addition to electric heat pumps, which have been commercially available for some time, increasing numbers of gas-fired sorption heat pumps have entered the market recently and represent a promising, climate-friendly heating technology for the future. Fraunhofer ISE has been working for many



years on the **development of new sorption materials and improved components (adsorbers, evaporators)** for adsorption heat pumps and sorption cooling systems, and supports manufacturers in all phases from development through to system evaluation in the field.

Our development work is supported by modelling based on fundamental thermodynamics, using both commercial software and programmes that have been developed at Fraunhofer ISE (**systems and detailed simulation**, CAD, CAM, CFD, etc.).

Transparent and reliable **measurement and evaluation methods** are essential for sustainable market development of all heat transformation processes. Recent technological and legislative innovations demand further development of existing evaluation methods and the preparation of new ones, both for components and for complete systems. Fraunhofer ISE is participating in numerous projects to develop and standardise such methods (e.g. IEA, VDI).

With the new **Testing and Development Centre for Heat Transformation**, which is equipped with the newest measurement technology and will start operation in the spring of 2014, we are expanding our infrastructure appreciably, allowing us to successfully implement innovative evaluation methods for all heat transformation processes, to support manufacturers in component and system development and thus assist heat transformation processes to improve their economic viability, increase their energy efficiency and penetrate larger markets.

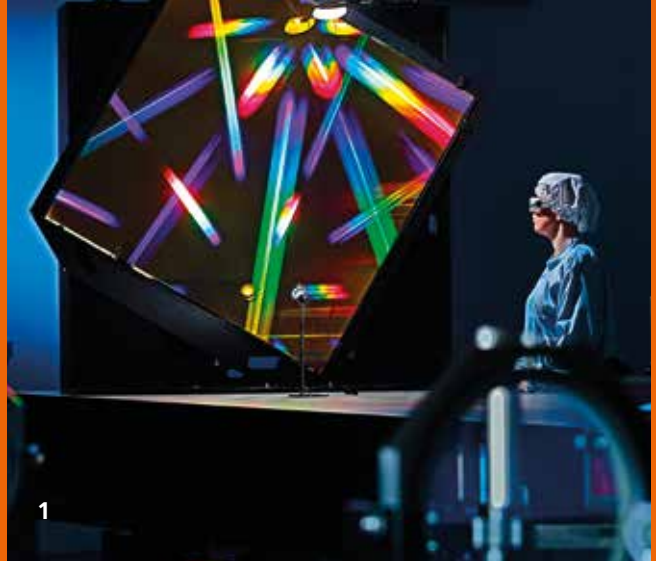
The establishment of the **Testing and Development Centre for Heat Transformation** was supported by the German Federal Ministry of Economics and Technology (BMWi).

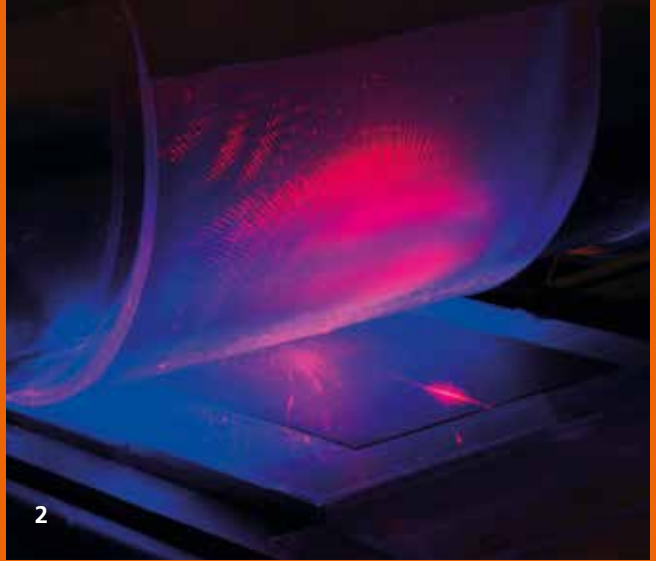
1 *Metal-organic framework materials allow sorption materials to be specificially optimised for different application cases.*

2 *Example of a stack configuration for an air cross-flow heat exchanger based on woven metal structures.*

3 *Side view of the test stand for fluid distributors at Fraunhofer ISE. In the test stand, the fluid distribution of a two-phase mixture, such as that needed in the evaporators of heat pumps and cooling systems, can be analysed quantitatively.*

4 *Completely installed heat pump system in a field test to determine efficiency coefficients continuously and to analyse the system behaviour.*





FUNCTIONAL MICROSTRUCTURES AND NANOSTRUCTURES OVER LARGE AREAS

FIELDS OF EXPERTISE
OPTICS AND PHOTONICS

Microstructured and nanostructured surfaces can make numerous optical and non-optical functionalities feasible. Preparation of such surface structures in customised forms and dimensions over large areas can be the basis for industrial implementation. The technology of interference lithography, which is well established at Fraunhofer ISE, offers unique possibilities. The architecture and infrastructure of the new laboratory building, which was officially opened in 2013, took the specific requirements of this technology into account. Measures implemented to improve the process stability mean that even more sophisticated structures can now be produced by interference lithography with still greater reproducibility and accuracy. The new laboratory building was financially supported by the German Federal Ministry of Education and Research (BMBF) and the Ministry of Finance and Economics of the State of Baden-Württemberg.

Benedikt Bläsi, Hubert Hauser, Oliver Höhn, Sabrina Jüchter, Volker Kübler, Eric Schneider, Christine Wellens, Werner Platzer

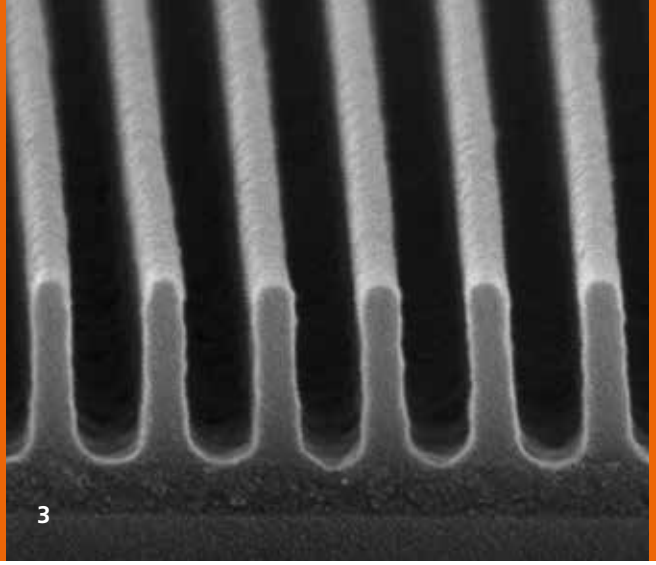
Structuring a surface to introduce new functionality can enable many effects. We concentrate particularly on photon management in optical systems such as solar cells, lighting systems, optical sensors or display applications. Our work addresses the complete chain from designing structures, through the production of master structures and replication, to characterization.

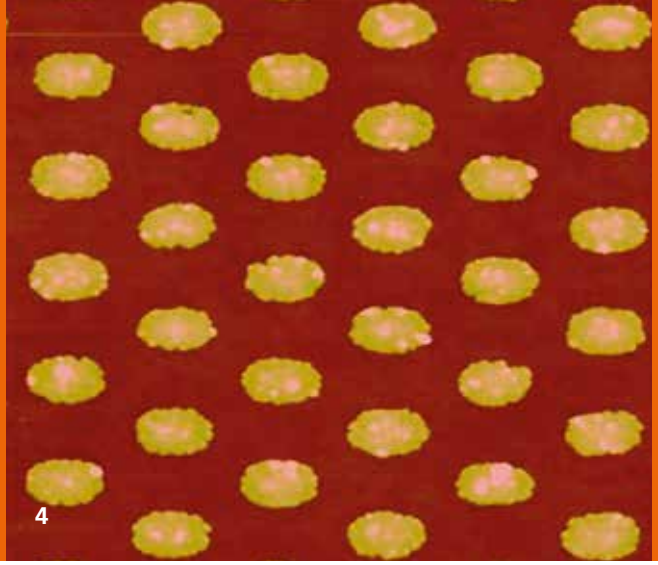
We use numerous **modelling tools** to reproduce effects by application of geometrical optics and wave optics. The goals are to understand optical effects of microstructured and nanostructured surfaces, on the one hand, and to formulate design specifications to implement customised functionality, on the other. In this field, it is particularly important to know which simulation approaches are relevant for specific applications and, if appropriate, to combine them as needed.

1 *Diffraction grating for photon management over an area of 1.2 x 1.2 m² in the new laboratory for interference lithography.*
2 *Structuring an etching mask for honeycomb texturing of a 125 x 125 mm² multicrystalline silicon substrate with the equipment developed at Fraunhofer ISE for roller nanoimprint lithography.*

In **interference lithography**, laser beams are split, expanded and then superimposed on a substrate which is coated with photoresist. The resulting interference pattern is then transformed by a development process into a surface structure of the photoresist. This technology allows us to produce seamless microstructures and nanostructures over areas of up to 1.2 x 1.2 m². Depending on specifications, the structure dimensions can be only 100 nm or up to 100 µm. The structures can be periodic or stochastic and a great variety of geometrical profile forms can be achieved, e.g. parabolic, binary or prismatic forms. In addition, multiple exposure allows the different configurations and geometrical forms to be combined with each other.

Microstructured surfaces are particularly interesting if they can be produced cheaply and in large quantities by **replication processes**. We are able to evaluate a great variety of replication processes for extremely diverse applications. A typical starting point is galvanic reproduction of the master structures which were created by interference lithography. In this way, initially a large number of metal copies can be made of one



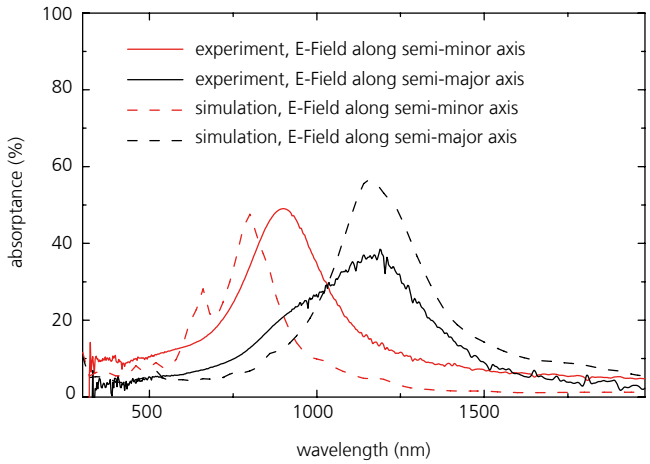


3 *Scanning electron microscopy image of a high-frequency linear grating with a large aspect ratio for light-guiding or polarisation-optical applications (period 230 nm).*

4 *Atomic force microscopy image of elliptical silver nano-particles to exploit plasmonic effects in solar cells. The particles can be produced in a well-defined form over a large area by a processing chain consisting of interference lithography, nanoimprint lithography, metallisation and lift-off. The particles have semi-major and semi-minor axes of 120 nm and 70 nm respectively, and are arranged hexagonally with a lattice plane separation of 300 nm.*

photoresist master. In turn, these can be used directly as embossing tools in hot embossing, injection moulding or roll-to-roll embossing processes. Alternatively, the metal copies can be used as templates to pattern flexible materials such as silicone derivatives. These flexible stamps can then be used as tools in so-called soft-embossing, micro-contact printing or nanoimprint lithography (NIL) processes. At Fraunhofer ISE, we have developed a roller NIL system which enables us to structure resist layers on rough, stiff and opaque substrates in an on-line process, e.g. as etching masks on multicrystalline silicon substrates.

An important aspect in the **characterization** of structured surfaces is to determine their geometrical configuration. Various microscopy methods are available to us, including optical, scanning electron and atomic force microscopy. Spectrometers and goniometers are used to measure the spectral and angle-dependent variation of different optical properties.



5 *Polarisation-dependent measurement and simulation of the absorptance spectra of the elliptical silver nano-particles on glass illustrated in Fig. 4. The polarisation directions are oriented parallel to the semi-axes of the particles. In this case, rigorous coupled wave analysis (RCWA) was used as the simulation method in order to reproduce wave-optical plasmonic effects.*

SERVICE UNITS

As a complement to our research and development work, we offer testing and certification services to clients. At present, Fraunhofer ISE has four accredited testing laboratories: TestLab Solar Thermal Systems, TestLab Solar Façades, TestLab PV Modules and the calibration laboratory with CalLab PV Cells and CalLab PV Modules. Our further service units include a battery test laboratory, an inverter laboratory, a lighting laboratory, test facilities for air / air and air / water heat exchangers, for heat pumps and evaporators, a laboratory for characterizing phase-change materials (PCM), a test laboratory for adsorbent and porous materials and a test centre for fuel cells. Furthermore, we are currently establishing a development and testing centre for heat transformation at Fraunhofer ISE. In future, electrically and thermally driven heat pumps will be measured and further developed there.

Beyond the service aspect, these units 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.

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

- test stand for solar air collectors
- hail test stand
- system and storage tank test stand
- outdoor test stand with trackers and a dynamic rack
- indoor test stand with a solar simulator (max. aperture area 3 x 3.5 m^2)
- collector test stand up to 200 °C
- mechanical test unit over an area of 5 x 3 m^2 in a climatic chamber

The main work of TestLab Solar Thermal Systems is based on commissions from the industry to test collectors, systems and tanks according to European and international standards or quality labels such as the "Solar Keymark" of CEN. A unique feature is the possibility to test collectors mechanically at temperatures between -40 °C and +90 °C (page 141).

TestLab Solar Façades was accredited according to DIN EN ISO/IEC 17025 in 2006. It offers a comprehensive range of characterization for innovative building components and materials to developers and planners of façades, façade components and windows, including shading devices. In particular, the range of services encompasses the characterization of components which also serve as active solar energy converters (e.g. transparent façade collectors and BIPV). In addition to accredited tests, comprehensive services concerning glare protection and daylighting are offered (page 142).

Testing of the following properties is included in the accreditation: g value (also calorimetric measurement), transmittance (spectral and broadband), reflectance (spectral and broadband) and U value.

TestLab PV Modules has been accredited since 2006 for type authorisation of PV modules according to IEC 61215 and IEC 61646 and since 2011 for the safety standard, IEC 61730. The goal of the test facility is quality control of PV module reliability. Within the framework of its cooperation with the VDE Institute, Fraunhofer ISE is responsible for all performance tests, while the VDE Institute carries out the safety tests and issues certificates after successful testing. In addition to the tests for product type approval, tests according to the manufacturers' specifications are also carried out to accompany the development of PV modules and module components (page 140). TestLab PV Modules cooperates closely with the calibration laboratory at Fraunhofer ISE, comprising CalLab PV Cells and CalLab PV Modules.

The fourth accredited laboratory, having gained this status in November 2006, is our calibration laboratory with CalLab PV Cells and CalLab PV Modules, which is one of the international leaders in this field. The calibration of photovoltaic modules plays an important role in product comparisons and for quality assurance of PV power plants. The cell calibration in CalLab PV Cells, which has been accredited as a calibration laboratory with the Deutscher Kalibrierdienst (DKD – German Calibration Service) since the end of 2008, serves as a reference for industry and research. The module calibration in CalLab PV Modules is part of the module certification process, on the one hand. On the other hand, it serves to control the quality of systems and to support development (pages 138/139).

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Long-term test of valves at low temperatures in a test cell integrated into a climatic chamber .

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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 for 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 an internationally leading photovoltaic calibration laboratory. 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**

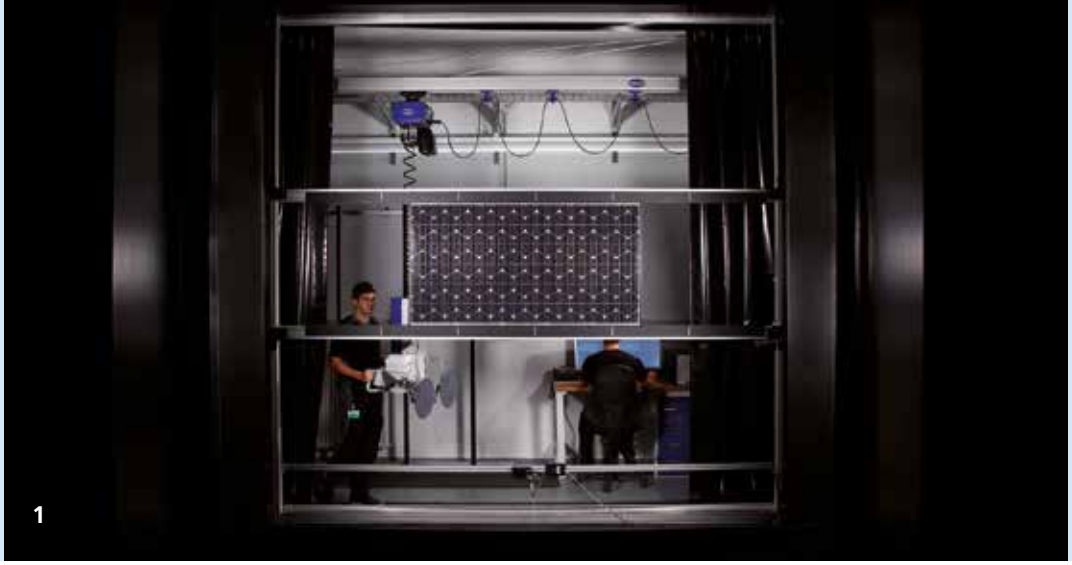
CalLab PV Cells is accredited according to ISO/IEC 17025 as a calibration laboratory for solar cell calibration with the Deutscher Kalibrierdienst (DKD). With the support of the German Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety (BMUB), and in cooperation with PV manufacturers, we work continuously on improving tolerances and developing new measurement procedures. For example, the change in solar cell parameters at higher temperatures plays an important role for their yield in practical application. A new procedure, with which temperature coefficients can be determined with a previously unattainable accuracy, has proven to be very attractive for manufacturers of solar cells. Its special feature is measurement of the temperature-dependent spectral response. We apply this and other special measurements intensively in a project to optimise 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 close cooperation with colleagues developing and analysing high-efficiency solar cells is an important prerequisite for this work. In order to guarantee the comparability of measurements for solar cells representing 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.

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

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, both within research projects and as a member of working group WG 7 of technical committee TC 82 of the IEC.



1

ACCURATE CHARACTERIZATION OF PV AND CONCENTRATOR PV MODULES

The internationally leading measurement accuracy of 1.8% at CalLab PV Modules means that the performance of PV modules can be determined very exactly. The high quality of our measurements was confirmed by an international comparison with leading laboratories around the world.

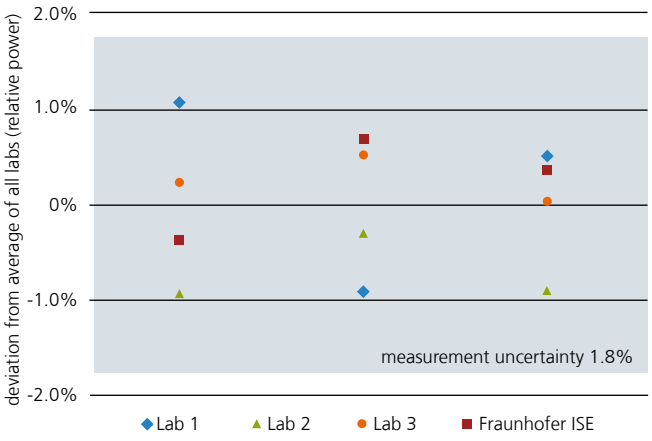
Daniela Dirnberger, Boris Farnung, Klaus Kiefer, **Frank Neuberger**, Michael Schachtner, **Gerald Siefer**, Harry Wirth

The high accuracy and quality of our power measurements was confirmed by an international comparison between leading laboratories, which CalLab PV Modules initiated and in which NREL in the USA, AIST in Japan and JRC in Italy also participated. With a tolerance band of less than one percent, the measurements made at Fraunhofer ISE are comparable around the world. The result underlines the internationally leading position of CalLab PV Modules, which has the lowest measurement uncertainty of 1.8% for the power value. Module manufacturers and investors can be sure that the measurements we make will be internationally comparable and recognised.

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.

Specific selection of module types for PV power plants also increases security for investors. Quality benchmarking is a procedure developed jointly by EPCs (engineering, procurement, construction) and distributors, for time-optimised and

1 *Accurate calibration of a PV module in CalLab PV Modules.*



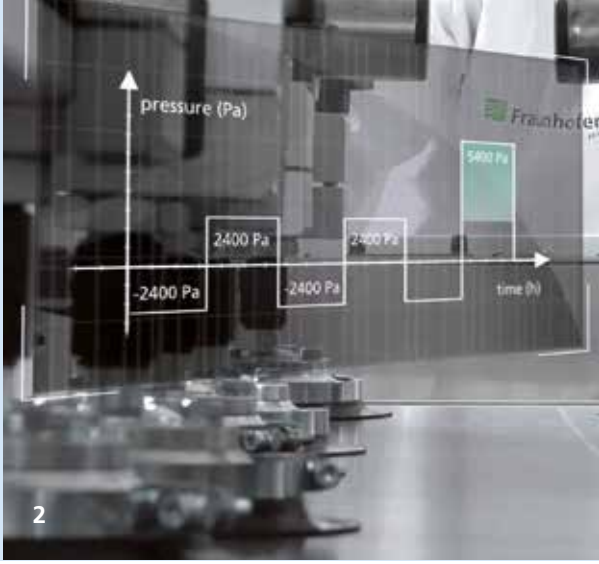
2 *The round robin comparison of the four internationally leading calibration laboratories for PV modules demonstrated that the deviation from the average for all participants was ± 1% and thus well within the measurement uncertainty of 1.8% for CalLab PV Modules.*

cost-optimised testing of PV modules. An individual testing procedure is derived from the client's quality specifications and the intended application area for the modules. The pre-defined pass / fail criteria lead to objective evaluation, independent of the manufacturer. In this way, CalLab PV Modules provides quality-control support to module manufacturers, EPCs and investors.

Measurement of Concentrator Modules

We operate several tracker units equipped with measurement data acquisition to characterize concentrator modules under outdoor conditions. In addition, we operate a laboratory test stand to measure concentrator modules. By participating actively in Working Group 7 of Technical Committee 82 of the IEC (International Electrotechnical Commission), we are further developing international standards on concentrator photovoltaics.

1



2

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 0.2 Hz).*

Assessment and Analysis of Defects, Risk Minimisation

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 analysing 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

TESTING AND DESIGN SUPPORT IN TESTLAB SOLAR THERMAL SYSTEMS

TestLab Solar Thermal Systems is recognised as an authorised 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 in developing solar thermal systems.

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

Since completion of our large test stand for mechanical loads in 2012, it has been used for numerous measurements commissioned by clients. 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). Its special features include the large testing area of 3 x 5 m², the possibility for applying heavy loads of up to 10 tonnes and reproduction of different load scenarios, e.g. cyclic loads, load gradients, dynamic loads.

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

Long and intensive work on our solar air-heating collector test stand was completed. With it, it is now possible to offer similar technical characterization to that for collectors with liquid heat-transfer media. In addition, the testing facilities for solar air-heating collectors were extended to accommodate models without covers.

1 *Scientists from Fraunhofer ISE TestLab Solar Thermal Systems working at the outdoor test field in Freiburg.*

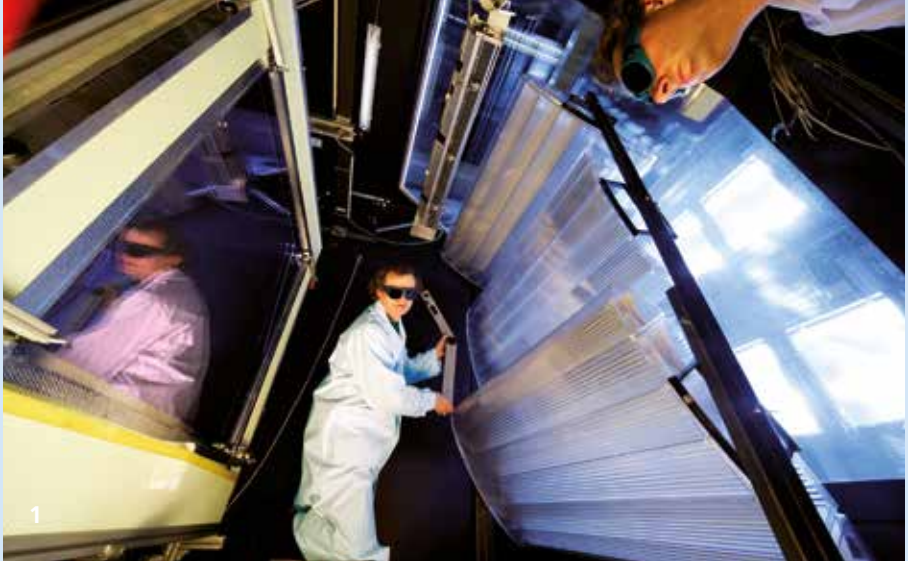
System investigations, particularly tank measurements according to DIN EN 12977, Parts 3 and 4, can be carried out in our systems and storage tank laboratory. This is where the coefficients are determined to evaluate tanks according to the Energy Label of the EU.

We have operated an indoor test stand with a solar simulator in TestLab Solar Thermal Systems since 2002. In 2012, we automated many aspects of laboratory operation, making it simpler for us 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. This means that experimental characterization of concentrating process-heat collectors (e.g. for solar thermally driven air-conditioning) is feasible in TestLab Solar Thermal Systems.

In 2013, many methodological further developments were introduced by our staff members to standardisation committees and will be implemented in new standards. In this way, TestLab Solar Thermal Systems meets its own expectations of not only testing but also defining and setting standards.

www.kollektortest.de



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. For façades for active use of solar energy (with photovoltaic and/or solar thermal components), we offer comprehensive characterization, 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 Unzeta, Johannes Hanek, Angelika Helde, **Tilmann Kuhn**, 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
- efficiency measurement
- thermal transmittance measurements (U-value) of glazing units
- angle-dependent transmittance and reflectance measurements with large integrating spheres, both broadband and spectral
- UV-vis-NIR spectrometers to determine the spectral properties of glass, films and surfaces

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

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

Daylighting Measurement Rooms

The daylighting measurement rooms consist of two identical office rooms, located side-by-side in a container. They can be rotated, so that any desired façade orientation can be chosen.
- glare protection tests
- user acceptance studies
- comparison of the lighting situation behind two façade systems

Façade Testing Facility

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

© Belectric

Quality Assurance of 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 from characterizing the components in our laboratories. The internationally unique measurement uncertainty of 1.8% 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, Laura Hardt, Klaus Kiefer, **Christian Reise,** Andreas Steinhüser, Harry Wirth

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

Battery Test Laboratory

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
Distributed storage of electricity in battery systems is becoming increasingly important. We test electric storage systems in a realistic environment, making use of solar simulators, diesel generators and our modern selection of inverters and charge controllers.

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

2 *Storage batteries, e.g. for the automotive sectors, can be tested at power values of up to 250 kW.*

Inverter Laboratory

The Inverter Laboratory at Fraunhofer ISE is equipped with all of the facilities which are needed to test central inverters up to a power rating of 1 MW according to diverse grid connection guidelines. A test facility for low-voltage ride-through on the medium voltage side enables us to investigate the reaction of inverters to short-term grid defects. Our highly accurate measurement technology makes it possible to determine reliably not only the conversion efficiency of inverters but also their MPP tracking behaviour.

In order to offer similar tests also for other generator units, we are equipped with a mobile voltage sag test container. It can be used to carry out low-voltage ride-through (LVRT) tests in solar parks, combined heat and power plants or wind power systems with a power rating of up to 4.5 MW.

Thanks to international cooperation, we are able to provide support concerning guidelines of the German BDEW and grid codes from other countries (China, Spain, Italy, etc.). In addition, we can offer our clients extensive simulation services in connection with certifying units and systems and addressing specific problems in PV parks.

Robin Grab, **Sönke Rogalla**, Günther Ebert

Lighting Laboratory

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

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

1 *The Inverter Laboratory offers detailed analysis of inverters up to a power rating of 1 MW with regard to performance and grid reaction.*

2 *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.*

SmartEnergyLab for Thermal-Electrical Building Energy Systems

As they become more economically attractive, distributed electricity generators are being installed in many residential buildings and provide electricity where it is consumed. Changes in the funding 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 stabilise the local grid.

The SmartEnergyLab 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. This means that any desired dynamic scenarios 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 SmartEnergyLab allows system providers to test and evaluate both their individual systems and also complete concepts in a realistic environment. 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

1 *Interior view of the SmartEnergyLab.*

Testing Facility for Heat Pumps

Several test stands are available to test compression heat pumps and evaporators with simulated typical sources and sinks (ground, ground water, outdoor air, exhaust air) (hardware-in-the-loop).

The power ranges we cover are from 0.5 to 3 kW for air-based heat pumps and 0 to 2 kW for cooling systems based on fluid-filled channels. A temperature range from -15 to 40 °C and a humidity range from 25 to 95% can be spanned when air is used as the source or sink medium. In hydraulically connected equipment and components, we achieve re-cooling power values corresponding to up to 12 kW heating power under steady-state conditions. In this case, the possible temperature range for sources and sinks is -15 to 90 °C. Furthermore, a test stand is available to characterize evaporators in a cooling power range of 1 to 6.5 kW.

The measurement is made in accordance with EN 14511 for space heating (or cooling) and according to EN 16147 (formerly EN 255-3) for domestic hot water heating combined with a tank. The evaporator test stand is oriented toward the specifications of EN 328. This test stand is authorised for flammable refrigerants (R290, R1270).

Simon Braungardt, Marek Miara, **Thore Oltersdorf**, Christian Sonner, Jeannette Wapler, Hans-Martin Henning

2 *Test stand to characterize evaporators for the R290 and R1270 refrigerants. The photo shows an air cooler being measured as a fin-pipe heat exchanger.*

Testing and Development of Heat Exchangers

Various test rigs are available to evaluate heat exchangers:
- air / water heat exchanger (air: 10–1200 m³/h for defined input humidity and temperature, water: 60–1800 l/h for defined input temperature)
- air / air heat exchanger (150–500 m³/h for defined input humidity and temperature, also suitable for open sorption)
- evaporator (for water and hydrocarbons as the working media) and adsorber (only water) (evaporation capacity up to 2.5 kW, adsorption capacity up to 8 kg)

The sensors installed in the test rigs allow the capacity, the thermal transmission and the heat transfer coefficients to be determined. The experimental expertise is complemented by simulation-based analysis. Depending on the question, tools such as COMSOL Multiphysics, OpenFoam, CoilDesigner, IMST-ART, Modelica or in-house software are used.

Further testing and simulation methods are available to investigate flow characteristics, fluid and temperature distributions and heat and mass transport, which allow the relevant factors to be identified for improved design of a heat exchanger.

Gerrit Füldner, Michael Herrmann, Alexander Morgenstern, Thore Oltersdorf, **Lena Schnabel**, Peter Schossig, Ursula Wittstadt, Hans-Martin Henning

PCM Laboratory: Characterization of Phase-Change Materials

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

Measurement instruments are also available to determine the following material parameters:
- thermal conductivity and thermal transmittance (K-value) of building components and wall constructions
- specific and latent heat storage capacity, nucleation temperature and supercooling by Calvet and heat-flux differential scanning calorimetry (DSC)
- cycling equipment
- adiabatic test room constructed according to DIN EN 14240 for static and dynamic measurement of heat and cooling systems
- test stands to prepare, characterize and cycle emulsions
- test cells with outdoor surfaces to measure PCM systems
- specially for characterization of phase change slurries (PCS):
  - density
  - thermal conductivity
  - particle size
  - viscosity
  - stability analysis

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

1 *Experimental set-up to measure the adsorption capacity and dynamics of adsorption heat exchangers.*

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

Test Laboratory for Porous Materials

The laboratories for thermal and structural analysis offer 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 characteristic 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.*

TestLab Fuel Cells

In our TestLab Fuel Cells, we characterize and test membrane fuel cells and systems with an electric power rating up to 20 kW_{el}.

In the characterization of fuel cells, we particularly emphasise the detailed investigation of local processes. With the help of our 68-channel system for spatially resolved electrochemical impedance spectroscopy of segmented single cells, we can analyse chemical-physical processes with regard to their dependence on materials, construction and operation management.

Our walk-in climatic chamber allows 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. To investigate the behaviour of a fuel cell 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 reliably by single cell monitoring from 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 and materials with respect to their electrochemical stability with a three-electrode configuration and by elemental analysis applying ICP-MS (inductively coupled plasma mass spectrometry).

Ulf Groos, Thomas Jungmann, Christopher Hebling

2 *Long-term test of valves at low temperatures in a test cell integrated into a climatic chamber.*

VISITING SCIENTISTS

Dr Jong-Deok An
Konkuk University Seoul, Korea, 4.3.2013–31.5.2013
Research area: Organic solar cells

Dr Hatem Bentaher
Higher Institute of Industrial Systems, Gabes, Tunisia, 1.7.2012–31.12.2013
Research area: Solar cooling

Federica Carluccio
Università del Salento, Lecce, Italy, 15.4.2013–15.10.2013
Research area: Modelling of sorption heat pumps

Dr Mete Cubukcu
Ege University, Solar Energy Institute, Izmir, Turkey, 2.5.2013–31.12.2013
Research area: Quality assurance for PV power plants

Julius Denafas
Baltic Solar Energy, Vilnius, Lithuania, 1.2.2012–31.1.2013
Research area: Production and characterization of metal contact structures

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

Simon Fey
Hochschule Offenburg, Offenburg, Germany, 1.9.2011–31.7.2014
Research area: Energy gateway

Prof. Benjamin Gonzalez-Diaz
Universidad de La Laguna, Tenerife, Spain, 1.4.2013–31.5.2013
Research area: Silicon thin-film

Prof. Ricardo Guerrero-Lemus
Universidad de La Laguna, Tenerife, Spain, 1.8.2013–31.8.2013
Research area: Silicon thin-film

Pedro Horta
University of Evora, Evora, Portugal, 5.2.2013–10.3.2013
Research area: Concentrating collectors

Dr Skander Jribi
University of Gabes / University of Sfax, Gabes, Tunisia, 14.6.2013–15.9.2013
Research area: Adsorption of alcohols and CO_2 on activated charcoal

Ankit Khanna
National University of Singapore, Solar Energy Research Institute of Singapore, Singapore, 18.3.2013–31.3.2014
Research area: Metallization of Si wafer solar cells

Sunae Lee
Konkuk University, Seoul, Korea, 4.3.2013–5.4.2013
Research area: Organic solar cells

Giuliana Leone
University of Palermo, Palermo, Italy, 1.9.13–31.12.13
Research area: Development of solar thermal façades

AnYao Liu
Engineering Building, Australian National University, Alton, Australia, 21.10.2013–15.11.2013
Research area: Analysis of defects in mc silicon

Prof. Louise Lomardo
Universidade Federal Fluminense, Niterói, Brazil, 1.3.2013–31.8.2013
Research area: Energy-efficient buildings in tropical climates

Rodrigo Lopes Sauaia
Pontifical Catholic University of Rio Grande do Sul, Porto Alegre/RS, Brazil, 1.12.2011–31.1.2013
Research area: Laser structuring with LCP

Prof. Daniel Macdonald
College of Engineering and Computer Service, The Australian National University, Canberra, Australia, 13.5.2013–13.7.2013
Research area: Characterization of impurities in silicon

Daniel Neves Micha
University of Rio de Janeiro, Rio de Janeiro, Brazil, 2.9.2013–31.8.2014
Research area: GaAs highest-efficiency solar cells

Dr Amada Montesdeoca-Santana
Universidad de La Laguna, Tenerife, Spain, 1.1.2013–31.1.2013
Research area: Crystalline silicon solar cells

Francisco Jose Moralejo Vazquez
CIEMAT – Photovoltaic Unit, Madrid, Spain, 1.9.2013–30.11.2013
Research area: Building integrated PV

Said Ould Amrouche
Centre de Développement des Énergies Renouvelables (CDER), Algier, Algeria, 28.10.2013–26.11.2013
Research area: Inverter Testing Laboratory

Salla Päivikki Repo
Aalto University, School of Electrical Engineering, Aalto, Finnland, 5.3.2012–31.5.2013
Research area: Material characterization and technology of Al_2O_3 and black silicon

Prof. Beatriz Romero
Universidad Rey Juan Carlos, Madrid, Spain, 15.7.2013–16.8.2013
Research area: Organic solar cells

Dr Alessio Sapienza
Consiglio Nazionale delle Ricerche (CNR), Istituto di Tecnologie Avanzate per l'Energia »Nicola Giordano« (ITAE), Messina, Italy, 7.6.2013–28.6.2013
Research area: Experimental characterization of the kinetics of adsorption heat exchangers

Aran Solé i Garrigós
GREA Innovació Concurrent, Universitat de Lleida, Lleida, Spain, 14.1.2013–17.4.2013
Research area: Cycling stability of sugar alcohols as latent heat storage materials

Emmerich Tempfli
Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany, 1.9.2013–31.12.2013
Research area: Energy efficiency, adsorption heat pump, heat exchanger development

Prof. Melkon Tatlier
Istanbul Technical University, Istanbul, Turkey, 1.10.2012–30.9.2013
Research area: Energy-efficient buildings

Richard Tuth
Badenova AG & Co. KG, Freiburg, Germany, from 1.8.2013
Research area: Determination of standard load profiles in the context of higher renewable energy penetration and optimisation of on-site electricity generation

Josip Vasilj
University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia, 5.6.2013–3.7.2013
Research area: SmartGrid

Prof. Mathias Wambsganß
Hochschule für Angewandte Wissenschaften, Fachhochschule Rosenheim, Germany, 1.11.2012–1.3.2013
Research area: Lighting technology and façades

Michiyo Yamane
Asahi Kasei Corporation, Advanced Energy Materials Development Center, Fuji, Japan, 1.4.2013–31.3.2014
Research area: Durability testing of polymer components for solar systems

Dr Nada Zamel
University of Waterloo, Waterloo, Canada, 1.10.2011–30.9.2014
Research area: Water management and fuel cells

DOCTORAL THESES

Monica Aleman
"Low temperature processes for the front-side metallization of crystalline silicon solar cells"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Constanze Bongs
"Experimentelle und mathematisch-numerische Untersuchung von verdunstungsgekühlten, sorptiv beschichteten Wärmeübertragern für die Luftentfeuchtung und -kühlung"
Technische Universität Berlin
Berlin, 2013

Luisa Burhenne
"Fixed Bed Biomass Gasification. Experimental investigation and modeling for the optimization of a novel process for the production of a tar-free product gas"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Sebastian Burhenne
"Monte Carlo Based Uncertainty and Sensitivity Analysis for Building Performance Simulation"
Karlsruher Institut für Technologie (KIT)
Karlsruhe, 2013

Marion Drießen
"Chemisches Gasphasenätzen und laterales epitaktisches Überwachsen für kristalline Silicium-Dünnschichtsolarzellen"
Universität Konstanz
Konstanz, 2013

Arne Fallisch
"Fabrication, Characterization and Modelling of Emitter Wrap-Through Silicon Solar Cells"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2012

Johannes Giesecke
"Quantitative Recombination and Transport Properties in Silicon from Dynamic Luminescence"
Universität Konstanz
Konstanz, 2013

Hubert Hauser
"Nanoimprint lithography for solar cell texturisation"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Henning Helmers
"Cogeneration of Photovoltaic Electricity and Heat Using Concentrated Solar Radiation"
Universität Oldenburg
Oldenburg, 2013

Thorsten Hornung
"Ein- und mehrstufige optische Konzentratoren für photovoltaische Anwendungen"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Ulrich Jäger
"Selektive Laserdiffusion für hocheffiziente Solarzellen aus kristallinem Silicium"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Vera Klinger
"Entwicklung von ultradünnen metamorphen Mehrfachsolarzellen zum Erreichen höchster Umwandlungseffizienzen"
Universität Konstanz
Konstanz, 2013

Philipp Löper
"Silicon Nanostructures for Photovoltaics"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Jan Nievendick
"Kontrolle und Weiterentwicklung des Texturierungsprozesses für multikristalline Silizium-Solarzellen"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2012

Teresa Orellana Perez
"Mechanical Behavior of Alternative Multicrystalline Silicon for Solar Cells"
Technische Universität Bergakademie Freiberg
Freiberg, 2013

Tobias Roesener
"Hocheffiziente III-V-Mehrfachsolarzellen auf Silicium Substrat"
Universität Konstanz
Konstanz, 2013

Marc Rüdiger
"Analysis and Simulation of Crystalline Silicon Solar Cells"
Universität Konstanz
Konstanz, 2013

Matthias Schicktanz
"Dynamische Modellierung einer Adsorptionskälteanlage unter besonderer Berücksichtigung des Einflusses von Temperaturfluktuationen"
Technische Universität Berlin
Berlin, 2013

Simon Schwunk
"Partikelfilter zur Ladezustands- und Alterungsbestimmung bei Lithium-Ionen-Batterien auf Basis von Metalloxiden und Phosphorolivinen"
FernUniversität Hagen
Hagen, 2013

Johannes Seiffe
"Plasma-Based Surface Modification Technologies for Crystalline Silicon Photovoltaics"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Wendelin Sprenger
"Electricity yield simulation of complex BIPV systems"
Technical University of Delft
Delft, 2013

Mark Steiner
"Energy Yield and Power Output Modeling for Analysis of CPV Modules"
Universität Oldenburg
Oldenburg, 2013

Felix Florian Stelzl
"2-dimensionales Donator/Akzeptor-Modell für organische Solarzellen und experimentelle Untersuchungen mittels Nanoelektroden"
Albert-Ludwigs-Universität Freiburg
Freiburg, 2013

Benjamin Thaidigsmann
"Entwicklung und Charakterisierung hocheffizienter MWT-PERC-Solarzellen aus p-dotiertem, kristallinem Silicium"
Eberhard Karls Universität Tübingen
Tübingen, 2013

Jochen Wirth
"Vergleich des Alterungsverhaltens verschiedener Dünnschichttechnologien in Photovoltaik-Modulen"
Universität Ulm
Ulm, 2012

MEMBERSHIP IN ORGANISATIONS

acatech – Deutsche Akademie der Technikwissenschaften

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

Bundesverband Energiespeicher (BVES), President

Deutsche Elektrotechnische Kommission (DKE):
- *Komitee 374 »Solarthermische Anlagen zur Stromerzeugung«*

Deutscher Wasserstoff- und Brennstoffzellen-Verband e. V. (DWV),

Energy Conservation Through Energy Storage Programme ECES:
- *Heat Pump Programme HPP*
- *Solar Heating & Cooling Programme SHC*

EU PV Technology Platform:
- *WG3 »Science, Technology & Applications«*
- *WG4 »Developing Countries«*

European Committee for Standardization (CEN):
- *TC 312 / WG 1 / WG 2 / WG 3 »Solar Collectors« / » Factory Made Systems« / »Thermal Solar Systems and Components«*

European Renewable Energy Research Centres Agency (EUREC)

European Solar Thermal Electricity Association (ESTELA) and Scientific Technical Committee

European Technology Platform on Renewable Heating and Cooling (RHC-platform), President

Fördergesellschaft Windenergie und andere Erneuerbare Energien (FGW) e. V.:
- *Arbeitskreis »Photovoltaik«*
- *Arbeitskreis »TR3 – Elektrische Eigenschaften und Erzeugungseinheiten«*
- *Arbeitskreis »TR4 – Modellierung und Validierung von Simulationsmodellen«*

ForschungsVerbund Erneuerbare Energien (FVEE)

Fuel Cell Europe

German Scholars Organization (GSO), President

International Advisory Committee of EUPVSEC

International Commission on Glass:
- *TC-10 »Optical Properties and Characterization of Glass«*

International Commission on Illumination CIE
- *TC3-39 »Discomfort Glare from Daylight in Buildings«*
- *TC3-47 »Climate-Based Daylight Modelling«*

International Electrotechnical Commission IEC:
- *TC-82 »Modules, non-concentrating«, WG2*

International Energy Agency IEA:
- *Solar Heating and Cooling Programme SHCP Task 39 »Polymeric Materials for Solar Thermal Applications«*

Solar Cluster Baden-Württemberg e.V. , Executive Board

Symposium Thermische Solarenergie, OTTI Technologie-Kolleg, Scientific Advisory Board

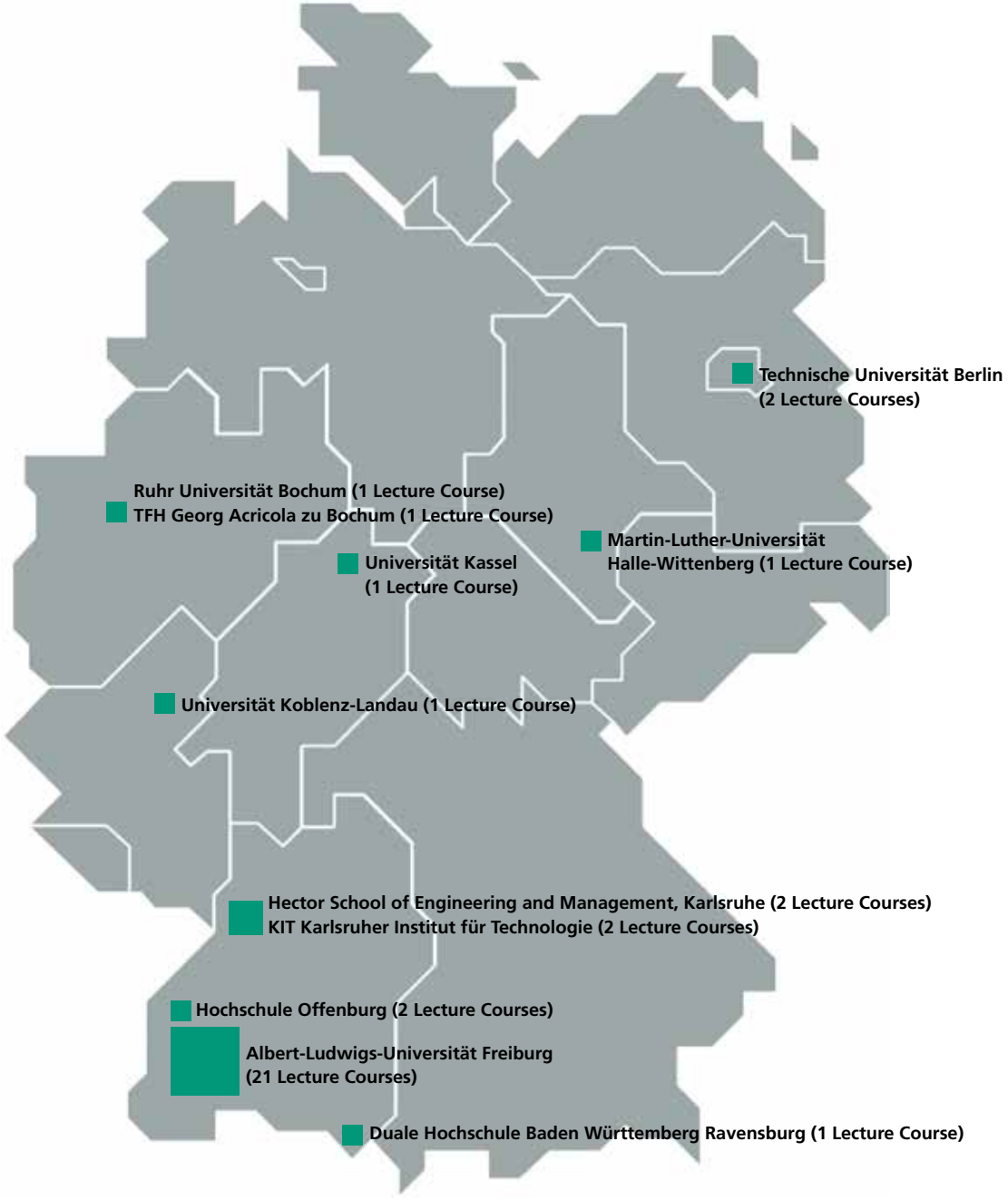
VDI-Gesellschaft Technische Gebäudeausrüstung (VDI-TGA):
- *Richtlinienausschuss 3789 »Energie und Umwelt«*
- *Richtlinienausschuss 4706 »Kriterien für das Innenraumklima«*
- *Richtlinienausschuss 4650, Blatt 1 und Blatt 2 »Wärmepumpen«*
- *Richtlinienausschuss 4645, »Planung und Dimensionierung von Wärmepumpen von Heizungsanlagen mit Wärmepumpen in Ein- und Mehrfamilienhäusern«*
- *Richtlinienausschuss 2164 »Latentspeichersysteme«*
- *Richtlinienausschuss 6018 »Kälteversorgung in der TGA – Planung, Bau, Abnahmeprüfung, Betrieb, energetische Bewertung«*

VDMA – The German Engineering Federation:
- *Arbeitskreis 24247 »Energie-Effizienz Kälteanlagen«*
- *Productronics Association*
- *Deutsches Flachdisplay-Forum (DFF)*
- *Organic Electronics Association (OE-A)*

Fraunhofer ISE is also active in numerous other organisations, associations and consortia.
www.ise.fraunhofer.de/en/about-us/organisations

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

PATENTS GRANTED

Farbstoffsensibilisierte photovoltaische Zelle, ein Verfahren zur Herstellung dieser photovoltaischen Zellen sowie deren Verwendung
Hinsch, Andreas; Kern, Rainer; Sastrawan, Ronald; Petrat, Frank Martin; Stützel, Burkhard; Schmidt, Friedrich Georg; Michael, Günther; Katusic, Stipan; Gutsch, Andreas
DE 102 49 246 B4

Anordnung mit Solarzelle und integrierter Bypass-Diode
Riesen van, Sascha; Löckenhoff, Rüdiger; Strobl, Gerhard; Dietrich, Ron; Koestler, Wolfgang
IL 183206

PKW-Klimaanlagen mit Adsorptionswärmepumpen
Henning, Hans-Martin; Mittelbach, Walter
KR 101 238 692 B1

Verfahren zur trockenchemischen Behandlung von Substraten sowie dessen Verwendung
Reber, Stefan; Willeke, Gerhard
US 8,569,175 B2

Wechselrichter mit integrierter Ansteuerung und Regelung für einen Tracker
Burger, Bruno; Lerchenmüller, Hansjörg
CA 2,671,962 C

Sonnenschutzvorrichtung mit winkelselektiver Transmission
Kuhn, Tilmann
JP 5350234 B2

Frontseitig serienverschaltetes Solarmodul
Löckenhoff, Rüdiger
EP 2 135 299 B1

Solarelement mit gesteigerter Effizienz und Verfahren zur Effizienzsteigerung
Goldschmidt, Jan Christoph; Löper, Philipp; Peters, Marius
US 8,507,790 B2

Textur- und Reinigungsmedium zur Oberflächenbehandlung von Wafern und dessen Verwendung
Mayer, Kuno; Schumann, Mark; Kray, Daniel; Orellana, Teresa Peres; Rentsch, Jochen; Zimmer, Martin; Kirchgäßner, Elias; Zimmer, Eva geb. Blazkow; Biro, Daniel; Rostas, Arpad Mihai
EP 2 229 431 B1

Verfahren zum Fertigen einer Silizium-Solarzelle mit einem rückgeätzten Emitter sowie entsprechende Solarzelle
Hahn, Giso; Haverkamp, Helge; Raabe, Bernd; Book, Felix; Dastgheib-Shirazi, Amir
US 8,586,396 B2

Steuerbare Umschaltvorrichtung für ein Solarmodul
Burger, Bruno; Schmidt, Heribert
CN 101821858 B, JP 5306362 B2

Thin-film solar cell and process for its manufacture
Mitchell, Emily; Reber, Stefan; Schmich, Evelyn
EP 2 071 632 B1

Verfahren zur Metallisierung von Solarzellen, Hotmelt-Aerosol-Tinte und Aerosol-Jet-Drucksystem
Hörteis, Matthias; Richter, Philipp; Glunz, Stefan
CN 101919063 B

Trennschaltung für Wechselrichter
Burger, Bruno; Schmidt, Heribert
JP 5303648 B2, KR 101314975 B1

Tandemsolarzelle aus kristallinem Silizium und kristallinem Siliziumcarbid sowie Verfahren zu dessen Herstellung
Janz, Stefan; Reber, Stefan
EP 2 351 108 B1

Heterosolarzelle und Verfahren zur Herstellung von Heterosolarzellen
Pysch, Damian; Glunz, Stefan
CN 102144303 B

Vorrichtung zur Verdampfung von flüssigen Kraftstoffen und brennbaren Flüssigkeiten, Verfahren zum Betreiben sowie Verwendungszwecke
Szolak, Robert; Susdorf, Alexander; Aicher, Thomas
DE 10 2010 012 945 B4

Verfahren zum Nachführen eines Solargenerators nach der Sonne, Steuerung für eine Solaranlage und Solaranlage
Burger, Bruno; Stalter, Olivier
CN 102422239 B

Mikroventil in keramischer Mehrlagentechnik sowie dessen Verwendung
Lenz, Bettina; Bromberger, Kolja
EP 2 340 386 B1

Abgasreinigungsvorrichtung, Verfahren zur Abgasreinigung, Katalysator sowie Pyrolysereaktor
Szolak, Robert; Susdorf, Alexander; Aicher, Thomas
DE 10 2010 049 957 B4

Aktiver Druckintensivierer, Umkehrosmose-Anlage und deren Verwendung
Went, Joachim; Anhalt, Julian
DE 10 2011 114 093 B4

Solarthermischer Kollektor
Henning, Hans-Martin; Dupeyrat, Patrick; Nunez, Tomas (†); Henninger, Stefan
DE 10 2011 112 974 B3

Verfahren und Vorrichtung zum lichtinduzierten oder lichtunterstützten Abscheiden von Metall auf einer Oberfläche eines Halbleiterbauelements sowie damit hergestelltes Halbleiterbauelement
Zimmer, Martin; Rentsch, Jochen; Savio, Christian; Könning, Clemens; Glunz, Stefan
DE 10 2012 214 925 B3

Method of forming a structure
Campe, Hilmar von; Schwirtlich, Ingo
JP 5 335 234 B2

Behälter zum Stapeln und Transportieren von Scheiben aus brüchigem Material
Warschatka, Andreas; Ries, Andreas
DE 10 2010 040 918 B4

Verfahren und Vorrichtung zur galvanischen Beschichtung von Substraten und Solarzellen
Lippert, Lothar; Caseday, Marcus; Reime, Sascha
DE 10 2010 042 642 B4

Photovoltaikmodule mit reduziertem Gewicht
Engelmann, Harry; Fliedner, Uwe; Nattermann, Kurt; Schwirtlich, Ingo
US 8,420,218 B2

Verfahren zur chemischen Behandlung eines Substrats
Teppe, Andreas; Schum, Berthold; Franke, Dieter; Schwirtlich, Ingo; Vaas, Knut; Schmidt, Wilfried
CN 102171798 B, EP 2 335 275 B1, US 8,563,440 B2

Method for producing a metal contact on a semiconductor substrate provided with a coating
Ernst, Ingrid; Schubert Gunnar; Horzel, Joerg; Roth, Peter; Dauwe, Stefan; Droste, Tobias; Schmidt, Wilfried
US 8,481,419 B2

Verfahren zur Herstellung von Wafern
Peip, Michael
DE 10 2008 037 653 B4

Wärmeisolationsanordnung mit variablem Wärmeisolationsvermögen und deren Verwendung sowie Vorrichtung und Verfahren zur Herstellung von ein- oder multikristallinen oder glasigen Materialien
Buellesfeld, Frank; Sahr, Uwe; Tittel, Andreas
EP 2 304 365 B1

Verfahren und Vorrichtung zum Führen eines Sägedrahtes
Berg, Michael; Bussemer, Beate; Loeber, Andreas; Martin, Rolf; Menzel, Andreas
DE 10 2011 055 006 B4

Verfahren zum Weiterverarbeiten und/oder Rezyklieren von Material
Buss, Werner; Campe Hilmar von; Schwirtlich, Ingo; Seidl, Albrecht
EP 2 141 121 B1, JP 5209507 B2

Verfahren und Vorrichtung zur galvanischen Beschichtung von Substraten
Lippert, Lothar; Dauwe, Stefan
DE 10 2009 029 551 B4

EDITORIAL NOTES

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Photo Acknowledgements

Belectric, Rolf Disch SolarArchitektur, Fraunhofer-Gesellschaft, Fraunhofer ISE, FWTM Freiburg, Fotolia, Kuweit Institute for Scientific Research, ModQS, Pixelio, Ryan Carter / Crown Prince Court – Abu Dhabi

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Adnan Al-Akori p. 97, Fig. 2; Michael Eckmann p. 39, p. 102/104, p. 105, p. 106, p. 111, p. 144, Fig. 1; Sven Ehlers p. 113; Thomas Ernsting p. 127, Fig. 2, p. 14; Matthias Heyde p. 1, p. 8/9; Myriam Kaiser p. 139; Guido Kirsch p. 13, p. 16/18, p.19, Fig. 2, p. 20, Fig. 2, p. 21, p. 73, Fig. 1; Thomas Klink p. 54/56, p. 58; Dirk Mahler p. 49, Fig. 1; Maria Parussel und Holger Vonder p. 132, Fig. 1; Joscha Rammelberg p. 88/90/92, p. 91, p. 93, p. 108/110, p. 120, p. 134/136, p. 147, Fig. 2; Daniel Schoenen p. 141; Thies Stillahn p. 94/96; p. 98, Fig. 1; Rainer Sturm p. 122/124; Alexander Wekkeli p. 46/48, p. 49, Fig. 2

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CONFERENCES AND TRADE FAIRS OUTLOOK 2014

10th SiliconFOREST Workshop, Feldberg-Falkau, Germany, 23.–26.2.2014

Photovoltaic Module Reliability Workshop (PVMRW), Golden, Colorado, USA, 25.–27.2.2014

Battery Expo and Fuel Cell Expo, Tokyo, Japan, 26.–28.2.2014

6. Forum Bauwerkintegrierte Photovoltaik (OTTI), Kloster Banz, Bad Staffelstein, Germany, 11.3.2014

KONGRESS-Forum ElektroMobilität, Berlin, Germany, 11.–12.3.2014

29. Symposium Photovoltaische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 12.–14.3.2014

Energy Storage, Düsseldorf, Germany, 25.–27.3.2014

7. Entwicklerforum Akkutechnologien, Battery University, Aschaffenburg, Germany, 26.–27.3.2014

4th International Conference on Crystalline Silicon Photovoltaics and PV Workshop, ´s-Hertogenbosch, Netherlands, 25.–28.3.2014

ISHPC 2014 International Sorption Heat Pump Conference, Maryland, USA, 31.3–3.4.2014

CPV-10, Albuquerque, USA, 7.–9.4.2014

Hannover Messe, Hanover, Germany, 7.–11.4.2014

2014 MRS Spring Meeting & Exhibit, San Francisco, USA, 21.–25.4.2014

24. Symposium Thermische Solarenergie (OTTI), Kloster Banz, Bad Staffelstein, Germany, 7.–9.5.2014

11th IEA Heat Pump Conference, Montreal, Canada, 12.–16.5.2014

8th SNEC PV POWER EXPO 2014, Shanghai, China, 20.–22.5.2014

11th PCIM Europe, Nuremberg, Germany, 20.–22.5.2014

Eurotherm Seminar N°99, Advances in Thermal Energy Storage, Lleida, Spain, 28.–30.5.2014

Intersolar Europe, Munich, Germany, 2.–6.6.2014

40th IEEE Photovoltaic Specialists Conference, Denver, USA, 8.–13.6.2014

5th International Flow Battery Forum IFBF, Hamburg, Germany, 1.–2.7.2014

Intersolar North America, San Francisco, USA, 7.–10.7.2014

The Battery Show, Novi, Detroit, USA, 16.–18.9.2014

20th SolarPACES, Beijing, China, 16.–19.9.2014

29th EUPVSEC, Amsterdam, Netherlands, 23.–25.9.2014

f-cell, Stuttgart, Germany, 6.–8.10.2014

6. Internationale Leitmesse für Elektro- & Hybrid-Mobilität eCarTec, Munich, Germany, 21.–23.10.2014

SHC Conference, Beijing, China, 27.–29.10.2014

Deutsche Kälte- und Klimatagung, Düsseldorf, Germany, 19.–21.11.2014

WCPEC-6, Kyoto, Japan, 23.–27.11.2014