Fraunhofer
ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2016/17

Cover photo and detail on page 5:
The rapidly developing, global photovoltaic market constantly demands technology which is more efficient and cost-effective. In order to produce high-efficiency PERC solar cells in series, Dr Jan Nekarda and Dr Ralf Preu developed the Laser-Fired Contact (LFC) Process, which can be integrated simply and inexpensively into existing production processes by solar cell manufacturers. They were awarded the Joseph von Fraunhofer Prize in 2016 for this achievement.

The back metal contact of currently manufactured solar cells, which is needed to conduct the generated electricity, usually covers the entire back surface of the silicon wafer. However, this limits the solar cell efficiency. A better performing alternative has been known since 1989, namely the Passivated Emitter and Rear Cell (PERC) technology. By developing the LFC process, the Fraunhofer researchers were the first to make industrial mass production of PERC solar cells feasible. A very thin, insulating layer is deposited on the back of a PERC cell between the contact layer and the wafer. This serves as a reflector for the share of sunlight which was not absorbed along its initial path through the silicon wafer. This radiation is reflected back into the wafer; as the same effect occurs at the front surface, the radiation is trapped in the silicon wafer and the solar cell efficiency increases. In order to conduct the generated electricity away from the wafer, many small openings in the insulating layer are needed, which allow contact to be established between the metal electrode and the silicon wafer. Applying the LFC process, the required contacts – about 100 000 in total – are made in one second, each contact by a single laser pulse. The PERC solar cells which are produced in this way have an efficiency value that is 1 % point higher than for conventional cells. This corresponds to a relative improvement of about 5 % for current solar cell efficiency values around 20 %.
A further relative gain of 2 % is made in the system, so that the overall electricity yield increases relatively by 7 %.

Director (until 31.12.2016)
Prof. Dr. Eicke R. Weber

FOREWORD

After more than ten years as the Director of Fraunhofer ISE, I am saying farewell with mixed feelings. I am happy to see my previous Deputy Directors, Prof. Hans-Martin Henning and Dr Andreas Bett, taking on the positions of Joint Acting Directors. They will bring fresh ideas to the important task of leading Fraunhofer ISE into the next decade. We talk together about the future of the Institute in a conversation recorded on pages 10 and 11 of this Annual Report.

On the other hand – and this is where sadness creeps in – I greatly enjoyed the task of directing this Institute, with its research that has been so influential on the global transformation of the energy system. It was a pleasure to lead this staff of more than 1100 today – during 2012 / 13 even peaking at 1300 – consisting of people who work with great personal interest on the topics of the energy transformation and engage themselves with much creative enthusiasm. One example among many – and of the "ISE Spirit" – is Prof. Bruno Burger, Head of the Power Electronics Group, who recognized that there was a deficit concerning reliable data on the situation of renewable energy in Germany. Parallel to his core work, he established the "Energy Charts", which are now downloaded thousands of times per year from the Internet. Our Board of Trustees frequently confirmed that our employees are our greatest treasure. I am happy that despite the major growth experienced over the past years, we have succeeded in maintaining this cooperative and also idealistic "ISE Spirit": We know that we are working at Fraunhofer ISE not only to earn our salaries but also to enable the transformation of the energy system to efficient utilization, finally of only renewable energy sources, technically and financially.

To keep our Annual Report manageable and transparent, we decided in 2015 that research projects at Fraunhofer ISE would no longer be presented individually, but instead that the activities addressed in the business areas would be summarized and linked to the numerous publications and project reports that are available on our web site. At this point, I would like to thank all members of our PR team under the leadership of Karin Schneider for their committed work, who have accompanied me so effectively during the past ten years at Fraunhofer ISE. I recognized early that public presence is very important for an institute of our size. It is necessary to address the public not only in scientific journals but also in generally accessible media, as public opinion finally decides which research topics will be supported. Consequently, I have always seen our publicity to have two goals: not only to present ourselves to our clients, particularly from the industry, but also to communicate our positions and opinions in interviews, guest articles and other activities in the public arena. Part of this strategy is that Fraunhofer ISE has also been present in social media since 2016, on Facebook and Twitter and with its own scientific blog. We are happy to enter into dialogue with you via these channels and comments, likes and posts.

In 2016, we were again able to celebrate a series of notable highlights recognizing our work. I would particularly like to mention the 30th anniversary of CalLab PV Cells with its excellent international reputation and also the 10th anniversary of our very successful PV-TEC, which will become even more effective due to the establishment of PV-Select in 2016. Dr Ralf Preu and Dr Jan Nekarda were greatly honored to receive the Joseph von Fraunhofer Prize for their work on Laser-Fired Contact technology LFC. In addition, we were happy to have a further professorship at Fraunhofer ISE, with Prof. Werner Platzer becoming an honorary professor. For my own part, I was pleased to be awarded the Rudolf Jäckel Prize of the Deutsche Vakuumgesellschaft.

In March 2016, we hosted a special workshop which addressed the transition of photovoltaics to a new phase, the terawatt era. At this event in Freiburg, we were able to greet

colleagues from the Global Alliance of Solar Research Institutes (GA-SERI), from the National Renewable Energy Laboratory (NREL), USA, and from the National Institute of Advanced Industrial Science and Technology (AIST), Japan.

Fraunhofer ISE not only conducts research on topics which are important for the global transition to a sustainable economy, but is also concerned that its own work is sustainable. Thus, we published our first sustainability report in 2016. We will address this topic again regularly in the future.

There are also many positive results from our research to be reported in 2016. With an efficiency value of 30.2 %, we broke through the 30 % "glass ceiling" for the efficiency of solar cells based on crystalline silicon. This success became feasible by wafer-bonding a III-V hetero-junction structure with a good Si solar cell, so that this cell can be contacted monolithically with only two external contacts. There was also a new world record in concentrator photovoltaics: We had already achieved a cell world record of 46 % for concentrating PV with III-V hetero-junction structures in 2016, but now this result has been complemented by a world record value of 43.4 % for a mini-module.

As one of his first ideas, the Institute's founding Director, Adolf Goetzberger had proposed "Agro-PV" projects, the combined usage of land for farming and photovoltaics. After a long lead-up period, a large test area started operation at the Demeter cooperative farm in Heggelbach in September 2016. The photo on page 58 / 59 shows this system in which the effect of PV "harvesting" on the growth of crops underneath a PV array will be investigated scientifically.

A number of other studies published by Fraunhofer ISE attracted public attention this year, e.g. one paper on a worldwide super-grid and another on the topic of a climate-neutral building stock in 2050. Newly forged formal cooperation initiatives can be reported: with NREL in the USA on the topic of hydrogen and fuel cells, with the French EDF Energies Nouvelles, with Transnet Baden-Württemberg and with Bosch on the subject of fuel cells. Fraunhofer ISE also became a new member of the "Climate Technology Centre & Network". As reported on page 78 of this Annual Report, we were able to allocate further finances within the Fraunhofer Zayed Program in 2016 for the seed funding of projects, particularly in developing countries. A total of 28 projects of this type have been funded to date.

Finally, I would like to combine special thanks with my farewell to our Trustees under the leadership of Dr Voigtländer. The very constructive Board Meetings gave me valuable feedback over the past ten years. Interesting new activities were initiated directly through discussions with the Board of Trustees. Of course, I also add my deep gratitude to all industrial partners of Fraunhofer ISE and funding bodies at the State, National and EU levels, which were essential for our success over the past ten years. For my own person, at the age of 67, I am ready to start something new and am looking forward to the interesting tasks which my Directorship of the "Berkeley Education Alliance for Research in Singapore BEARS" will bring starting in 2017.

OUR VISION

Fraunhofer Institute for Solar Energy Systems ISE conducts applied research and development to promote a sustainable, economic, safe and socially just energy supply system for the whole world.

OUR MISSION

The Institute develops technical solutions to use renewable energy sources economically and to increase energy efficiency. With its systems-oriented and technological innovations, it contributes to the competitive strength of its clients and to social acceptance of sustainable energy systems. Fraunhofer ISE aims to occupy and further expand an internationally leading position as a research institute dedicated to efficient and solar energy systems by generating excellent research results, carrying out successful projects, cooperating with partners and founding spin-off companies. In this way, it intends to contribute to the transformation of the energy supply system until finally only renewable energy sources are used efficiently. The Institute cooperates with renowned partners from around the world to achieve optimal results. Our goal is to combine excellent scientific research and development with economic success, industrial implementation and technical progress.

OUR FOUNDATION

Fraunhofer ISE is the largest solar energy research institute in Europe. Its successful work is based on seven pillars, which define the Institute's understanding of itself:

- Excellently qualified and motivated staff
- Modern, high-performance research infrastructure
- Broad spectrum of topics and systems competence
- Many years of experience and expertise
- Recognized competence in analysis and testing
- Successful, project-funded business model
- National and international cooperation

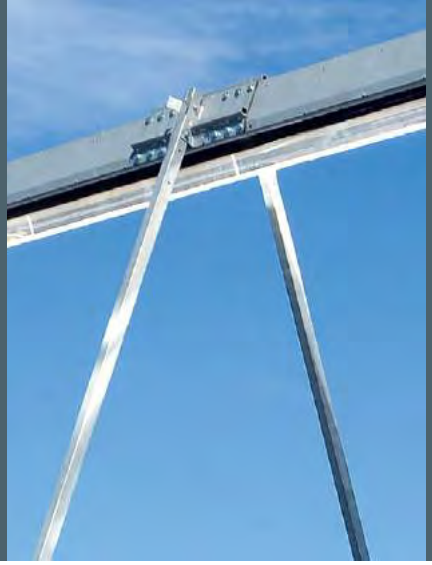

TABLE OF CONTENTS



ORGANIZATIONAL STRUCTURE

The organizational structure of Fraunhofer ISE is defined, apart from Business Administration, Facility Management and staff units, by eight scientific divisions: Thermal Systems and Building Technology; Electric Energy Systems; Solar Cells – Development and Characterization; PV Production Technology and Quality Assurance; Hydrogen Technology; Solar Thermal Technology and Optics; Photovoltaic Modules, Systems and Reliability; Materials – Solar Cells and Technology.

Five market-oriented business areas are used for external representation:

- Photovoltaics
- Solar Thermal Technology
- Building Energy Technology
- Hydrogen Technologies
- Energy System Technology

Until 31.12.2016, the Institute Directorate consisted of Prof. Eicke R. Weber, Dr Andreas Bett, Prof. Hans-Martin Henning, Dr Sonja Reidel and Jochen Vetter. Since 01.01.2017, the Institute Directorate has consisted of Prof. Hans-Martin Henning, Dr Andreas Bett, Dr Sonja Reidel and Jochen Vetter.

Fraunhofer ISE is supported by long-standing mentors and experts in the solar energy sector acting as consultants: 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).

Institute Director(s)

Prof. Eicke R. Weber
until 31.12.2016

Prof. Hans-Martin Henning (Acting Director)
+49 761 4588-5134 · from 01.01.2017

Dr Andreas Bett (Acting Director)
+49 761 4588-5257 · from 01.01.2017

Deputy Directors

Prof. Hans-Martin Henning
until 31.12.2016

Dr Andreas Bett
until 31.12.2016

Chief Administrative Officer
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Chief Facility Management Officer
Jochen Vetter + 49 761 4588-5214

Press and Public Relations
Karin Schneider M.A. +49 761 4588-5150

Energy Policy
Gerhard Stryi-Hipp +49 761 4588-5686

(from left to right): Dr Andreas Bett, Deputy Director and Business Area Coordinator for "Photovoltaics" until 31.12.2016 and Acting Institute Director from 01.01.2017; Jochen Vetter, Facility Management; Karin Schneider, Press and Public Relations; Prof. Eicke R. Weber, Institute Director until 31.12.2016; Prof. Hans-Martin Henning, Deputy Director and Business Area Coordinator for "Building Energy Technology" until 31.12.2016 and Acting Institute Director from 01.01.2017; Dr Sonja Reidel, Business Administration.

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 2016).

BOARD OF TRUSTEES

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Dr Carsten Voigtländer
Vaillant Group, Remscheid

DEPUTY CHAIRMAN

Dr Hubert Aulich
SC Sustainable Concepts GmbH, Erfurt

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Oliver Baudson
TSK Flagsol GmbH, Cologne

Dr Klaus Bonhoff
NOW GmbH, Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie, Berlin

Ullrich Bruchmann
German Federal Ministry for Economic Affairs and Energy (BMWi), Berlin

Dr Christian Buchner
Schmid Technology Systems GmbH, Freudenstadt

Martin Eggstein
State Ministry of the Environment, Climate Protection and the Energy Sector, Baden-Württemberg, Stuttgart

Daniel Etschmann
Kreditanstalt für Wiederaufbau, Frankfurt

Hans-Josef Fell
Energy Watch Group (EWG), Hammelburg

Burkhard Holder
VDE Prüf- und Zertifizierungsinstitut GmbH, Offenbach

Helmut Jäger
Solvis GmbH & Co. KG, Braunschweig

Günther Leßnerkraus
State Ministry of Finance and Economics, Baden-Württemberg, Stuttgart

Sylvère Leu
Meyer Burger Technology AG, Gwatt, Switzerland

Dr Dirk-Holger Neuhaus
SolarWorld Innovations GmbH, Freiberg

Dr Norbert Pralle
Ed. Züblin AG, Stuttgart

Dr Klaus-Dieter Rasch
AZUR SPACE Solar Power GmbH, Heilbronn

Prof. Leonhard Reindl
University of Freiburg, Freiburg

Prof. Frithjof Staiß
Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), Stuttgart

Dr Norbert Verweyen
RWE Effizienz GmbH, Dortmund

Prof. Andreas Wagner
Karlsruhe Institute of Technology (KIT), Karlsruhe

CHANGE IN THE INSTITUTE DIRECTORATE – REVIEW AND OUTLOOK

In conversation (from left to right): Prof. Eicke R. Weber, Director of the Institute from 01.07.2006 to 31.12.2016, and Prof. Hans-Martin Henning together with Dr Andreas Bett, Joint Acting Directors from 01.01.2017:

Weber: I was very fortunate to be the Director of Fraunhofer ISE in one of the most exciting phases in the history of the global solar sector. In 2006, PV plants with a total power of a few 100 MW were installed each year; today the annual figure is 60 GW. The rapid development enabled us to increase our operating budget from 25 million to 75 million euros, and allowed our staff to grow from 500 to more than 1100. Our technological advances resulted in many milestones and efficiency records being achieved, such as 46 % for concentrator solar cells, 99 % for inverters and recently breaking through the 30 % ceiling for a silicon-based multi-junction solar cell. Within the Institute, I initiated structural changes which allowed four PV divisions to develop excellently from one single photovoltaic department. My personal strategy was to deliberately delegate responsibility to allow the Institute to grow dynamically in the context of the dramatic market growth. This included the transition from departments to divisions, with each of their Heads carrying major responsibility. In my opinion, this was the secret behind the dynamic growth of Fraunhofer ISE over the past ten years.

Henning: I agree with you completely, but also see that we still need many further system components to advance the energy transformation, such as storage elements, highly energy-efficient technology and thermal applications of solar energy, among other aspects, which are being addressed by Fraunhofer ISE and which will become much more significant in the next few years. Consequently, many other technological fields will play a growing role in addition to the photovoltaic pillar, which will continue to be important. These include battery technology, power electronics or hydrogen production with the various associated technologies such as the conversion of hydrogen back into electricity in fuel cells or further reaction with carbon dioxide to produce gaseous or synthetic liquid fuels. We have been working on these topics for many years, but it is only today that their significance is being recognized. Here, we must ensure that our Fraunhofer Institute is at the head of the field when commercial implementation and sustainable market development are on the agenda.

Weber: Yes, and what is really great is that Fraunhofer ISE has been prepared for this since its foundation, as the research spectrum was already defined in the 1980's – a far-sighted achievement of our predecessors. It allows the Institute to adapt flexibly to market requirements. The overall trend is to replace fossil and nuclear fuels by renewable energy sources. This will happen; it is only a question of how quickly and in which country. And for me – and also for the new Institute Directorate – it will be a great challenge to ensure that we continue to be at the forefront of this development, that we do not relinquish this position to others. We have the necessary technologies. Although the market in Germany has shrunk, the global market is growing. This challenge applies not only to research, but also to politics and industry.

Henning: I see that we are excellently positioned to take up this challenge. I believe that we still have potential to exploit by further strengthening cooperation between our scientific divisions, which indeed still work quite independently of each other. Specifically when it comes to topics concerning whole systems, it is essential that distributed competence be united, so that major questions which are not restricted to a single technology can be addressed. Fraunhofer ISE has much to offer in this respect. Thus, one of the tasks for the new Institute Directorate will be to find ways and means to further promote internal networking.

Bett: Of course, photovoltaics still has a lot to offer also. We are excellently prepared for the next step. What will come after the silicon solar cell? The answer is multi-junction solar cells with higher efficiency for lower cost. No other institute anywhere in the world provides better pre-requisites to meet this challenge. Prof. Weber has already mentioned the record efficiency value of 46 % with multi-junction solar cells based on III-V semiconductors. In the silicon sector also, our TopCon technology currently holds the efficiency record of 25.3 % for a solar cell with contacts on both surfaces. We will unite the two technological approaches. Developments on perovskite materials and the integration of solar cells into modules offer further avenues. Here, there is still much to be developed and transferred to industrial production. The R&D work in photovoltaics has certainly not finished yet. Thus, we are investing and are currently building a center with optimized clean-room technology for highest-efficiency solar cells. The center will enable us to advance further in optimizing efficiency and costs. We are transferring competence which we have established in the PV sector to other technological fields. For example, our experience with PV production technology means that we can contribute a lot to the subject of batteries, which is currently a very active area of international research.

Henning: That is correct, and then, of course, we should not forget the building topic. Buildings consume a good third of the end-consumer energy in Germany – there is an enormous amount to be gained here with both the building envelope and the building technical services. For the building envelope, there is the question of not only making energy efficiency more cost-effective, but also of using the envelope as an active energy converter. The challenge to building technical services is to meet the residual energy demand with renewable energy sources, for example by applying heat pumps optimally – using electricity from renewable sources wherever possible – and simultaneously meeting external system requirements. These are all topics which Fraunhofer ISE has been addressing for many years and which are becoming more significant. We are already very well prepared technologically. However, we can still do more with regard to energy systems analysis and energy systems technology.

Weber: Exactly – that is a field where you, Prof. Henning, have already made an excellent contribution with the "REMod-D" investigation of the German energy system, in which model routes to implement the energy transformation have been analyzed, including detailed economic evaluation. This is a wonderful example for the way in which the transition to the new Institute Directorate – based on the strengths developed over the past years – offers new opportunities. I am convinced that Fraunhofer ISE will become one of the absolute leaders for energy systems analysis in the near future.

Bett: And this will be on the international stage, because at present, more is happening elsewhere in the world than in Germany. We will certainly see our work becoming more international in the coming years. Important indicators are e.g. the intention expressed by numerous developing countries at the Climate Change Conference in Marrakesh to meet 100 % of their energy demand from renewable sources by 2040. We must succeed in bringing our offers to the market and clients around the world and demonstrating what we can contribute.

Henning: In doing so, we will certainly not forget that German economy is extremely important for us. In my opinion, the opportunities for German industry to play a leading role in developing technology to transform our energy systems – in Germany and globally – have not been recognized sufficiently yet.

Weber: And I can promise that the Fraunhofer connection will continue, as far as I am concerned. As a professor of UC Berkeley, I will become the Director of the "Berkeley Education Alliance for Research in Singapore BEARS", a program between Berkeley and the National University of Singapore, which particularly addresses energy transformation topics. In this context, I will not forget the competence offered by Fraunhofer ISE.

FRAUNHOFER-GESELLSCHAFT

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

At present, the Fraunhofer-Gesellschaft maintains 67 institutes and research units. The majority of the nearly 24,000 staff are qualified scientists and engineers who work with an annual research budget of more than 2.1 billion euros. Of this sum, more than 1.8 billion euros is generated through contract research. More than 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Almost 30 percent is contributed by the German federal and Länder governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies and helping to train the urgently needed future generation of scientists and engineers.

As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

1 *The premises of the Fraunhofer-Gesellschaft in Munich, Germany.*

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

The Fraunhofer Institute for Solar Energy Systems ISE, which was founded in Freiburg, Germany in 1981, is the largest solar energy research institute in Europe with a staff of more than 1100. It creates technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. With its research focusing on energy conversion, energy efficiency, energy distribution and energy storage, it contributes to a broad application of new technology.

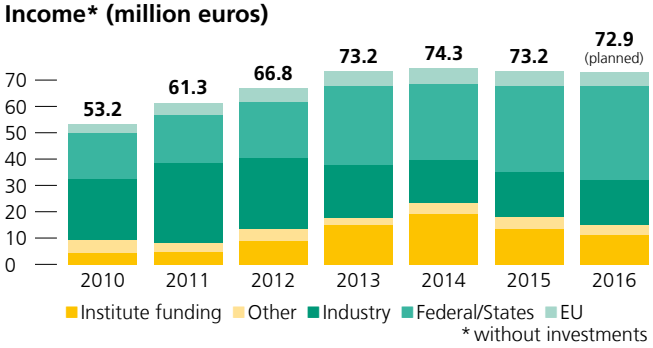
Together with clients and partners from industry, politics and society in general, Fraunhofer ISE develops technical solutions that can be implemented in practice. It investigates and develops materials, components, systems and processes in five business areas. Its innovative strength is documented, among other indicators, by the large number of patent applications. The Institute also offers testing and certification services. Fraunhofer ISE is certified according to the quality management standard, DIN EN ISO 9001:2008.

The Institute finances itself to 84 % 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.

The financial structure of the Fraunhofer-Gesellschaft distinguishes between operational and investment budgets. The operational budget includes all expenses for personnel and materials, as well as their financing with external income and institutional funding. In 2016, our operational budget totalled 72.9 million euros. In addition, the Institute made investments of 8.2 million euros in 2016 (not including investments for building construction and the economic stimulus program).

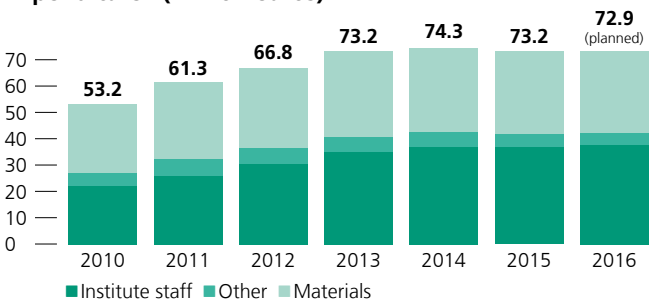
On 31st December 2016, a total of 1163 staff members were employed at Fraunhofer ISE. Included in this total are 124 doctoral candidates, 115 diploma/masters students, 20 guest scientists, 33 trainees and 250 scientific assistants.

Income* (million euros)



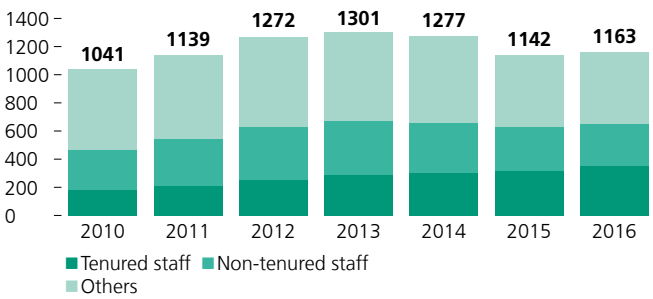
* without investments

Expenditure* (million euros)



* without investments

Personnel



EXTERNAL BRANCHES AND COOPERATIONS

In addition to its headquarters in Freiburg, Fraunhofer ISE has three external branches in Germany and specific collaboration with two international bodies.

Laboratory and Service Center, Gelsenkirchen LSC
The Fraunhofer ISE Laboratory and Service Center LSC, which was founded in 2001, specializes in the development of production-relevant processes to manufacture thin-film silicon solar cells, silicon hetero-junction solar cells and multi-crystalline silicon solar cells. It has two excellently equipped technological divisions and possesses comprehensive measurement facilities to characterize thin films and solar cells.

Fraunhofer Center for Silicon Photovoltaics CSP
The Fraunhofer Center for Silicon Photovoltaics CSP in Halle / Saale was jointly founded by the Fraunhofer Institute for Microstructure of Materials and Systems IMWS in Halle and Fraunhofer ISE. The main research work is carried out in two groups, one addressing Reliability and Technologies for Grid Parity (CSP-ZTN) and the other being the Laboratory for Crystallization Technology (CSP-LKT). Together with the Silicon Materials Technology and Evaluation Center SIMTEC at Fraunhofer ISE in Freiburg, the latter group provides a comprehensive technological platform for industrially relevant crystallization processes applying modern industrial-type equipment.

Technology Center for Semiconductor Materials THM
Fraunhofer THM in Freiberg addresses the production of crystalline materials and the mechanical separation of the produced bulk material. It supports companies with contracted work and within publicly funded projects in materials preparation, processing and characterization, including crystal growth, wafer production, epitaxy and selection of additives. Fraunhofer THM has operated since 2005 as a joint department of Fraunhofer ISE and Fraunhofer IISB.

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). Expertise and technology in the field of renewable energy that is already established in Europe is further adapted and introduced to the American market by Fraunhofer CSE. Together with the Canadian Standards Association (CSA), Fraunhofer CSE is operating a test facility for PV modules, the CFV Solar Test Laboratory, which is located in Albuquerque, New Mexico.

Fraunhofer Chile Research – Centro para Tecnologías en Energía Solar
The Centro para Technologías en Energía Solar (Fraunhofer Chile Research-Center for Solar Energy Technology FCR-CSET) offers research and consultancy services to the Chilean solar industry and politics. Scientists from Fraunhofer ISE, the Pontificia Universidad Católica de Chile and other Chilean universities are conducting research there particularly on the solar generation of electricity and process heat as well as on water purification.

Networking within the Fraunhofer-Gesellschaft
- Fraunhofer Alliances: Energy, Batteries, Building Innovation, Nanotechnology, Space and Water Systems (SysWasser)
- Fraunhofer Electromobility Systems Research
- 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"

1 *Centro para Tecnologías en Energía Solar (FCR-CSET) in Santiago, Chile.*
2 *Fraunhofer Center for Silicon Photovoltaics CSP in Halle/Saale, Germany.*

Fraunhofer ISE conducts application-oriented research and development for key renewable energy technologies of the future. To this purpose, the Institute addresses a wide range of subjects and pursues a holistic, systemic approach. This maximizes synergy between the five business areas of the Institute.

SPECTRUM OF ACTIVITIES

BUSINESS AREAS

Photovoltaics (Seite 16)
- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Emerging Photovoltaic Technologies
- Photovoltaic Modules and Power Plants

Solar Thermal Technology (Seite 38)
- Materials Research and Optics
- Thermal Collectors and Components
- Thermal Systems Engineering
- Thermal Storage for Power Plants and Industry
- Water Treatment

Building Energy Technology (Seite 44)
- Building Envelope
- Heating and Cooling Technologies
- Energy Concepts and Building Performance Optimization
- Thermal Storage for Buildings
- Materials and Components for Heat Transformation

Hydrogen Technologies (Seite 52)
- Thermochemical Processes
- Hydrogen Production by Water Electrolysis
- Fuel Cell Systems

Energy System Technology (Seite 58)
- Power Electronics
- Smart Grid Technologies
- System Integration – Electricity, Heat, Gas
- Battery Systems for Stationary and Mobile Applications
- Energy System Analysis

R&D ACTIVITIES

In our research activities, we develop new products, processes or services, and optimize existing ones. To do so, the Institute finds promising technical solutions and transfers technology from science and research to industry and society at large. As a partner for industry, the Institute orientates itself according to our clients' requirements and contributes toward their economic value generation. By cooperating with Fraunhofer ISE, enterprises without their own large R&D department gain access to high-performance laboratory infrastructure and excellent research services. We carry out research and development projects at various phases in the life cycle of a given technology. Depending on the task and requirements of our clients or the technological maturity of the subject, the Institute offers services in various forms*:

- New material / process
- Prototype / pilot series
- Patent / licence
- Software / application
- Measurement-based analysis / quality control
- Advice / planning / studies

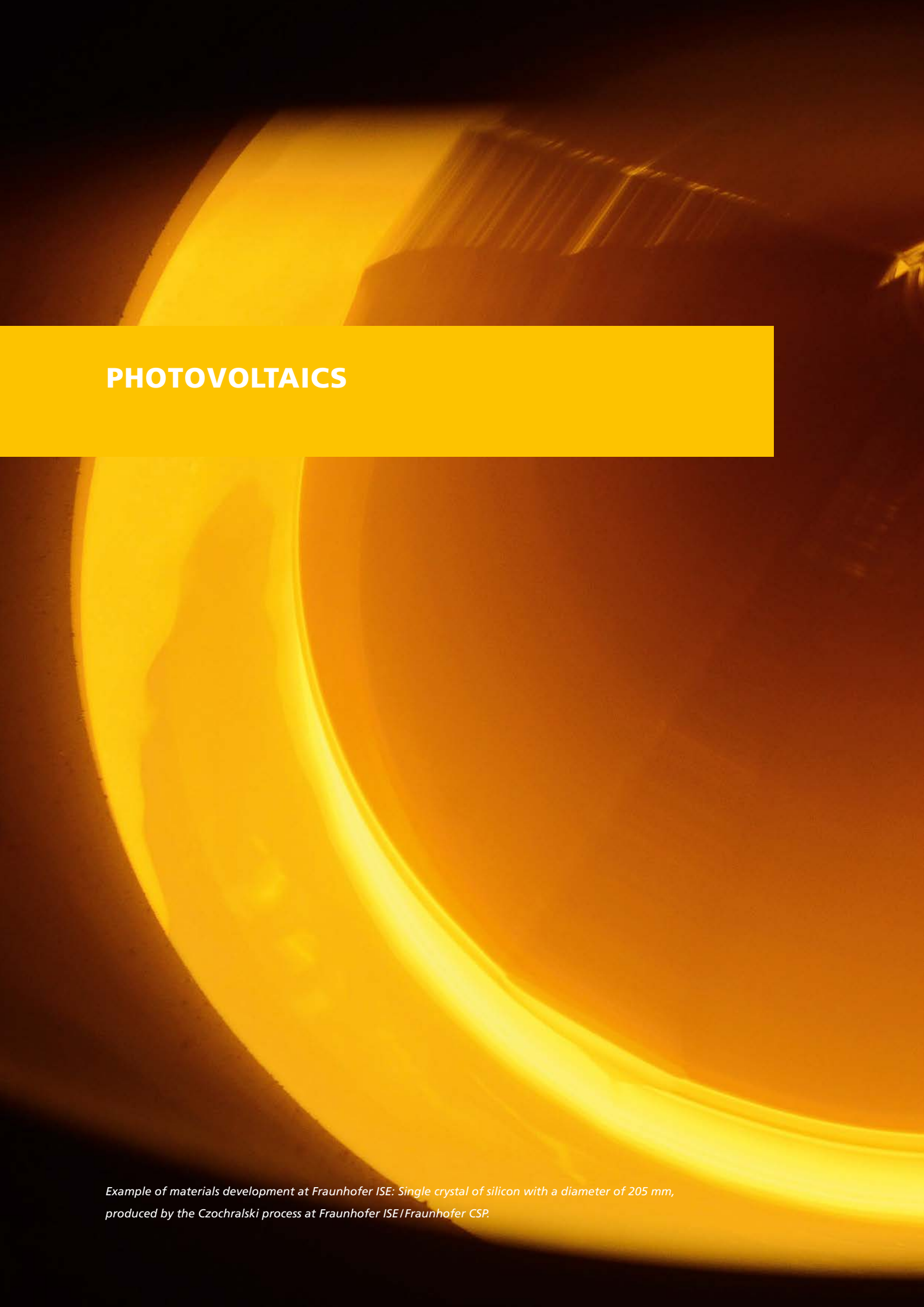
SERVICE UNITS (Seite 64)

Complementing our research and development work, Fraunhofer ISE operates 16 service laboratories, which cover the entire bandwidth of research subjects addressed at the Institute. These include six accredited testing or calibration laboratories. The laboratories offer services to the industry, each based on its specific set of measurement and testing equipment. At the same time, these laboratories also have a research function, as the insights gained during characterization, certification or testing can also be used in R&D projects.

1 *Main building of Fraunhofer ISE in Freiburg, Germany.*

* *The project reports from the business areas are classified according to these categories.*

PHOTOVOLTAICS



Example of materials development at Fraunhofer ISE: Single crystal of silicon with a diameter of 205 mm, produced by the Czochralski process at Fraunhofer ISE / Fraunhofer CSP.

Photovoltaic technology is an essential pillar for transforming our energy system into one based on renewable and sustainable energy sources. Analyzes and models prepared by Fraunhofer ISE demonstrate clearly that the energy transformation cannot occur without tapping the enormous potential offered by photovoltaics. It is thus essential that photovoltaic technology continue to be developed further. The technical progress so far and scaling effects of mass production have resulted in a recent reduction in the levellized cost of electricity from photovoltaics, which had been considered impossible previously. One consequence is world-wide growth of the photovoltaic market. In 2015, PV with a total rated power of 59 GWp was installed, which corresponds to an increase of 35 % compared to the previous year. However, only 1.4 GWp was installed in Germany, about 26 % less than in 2014. After years of excess production capacity, the photovoltaic sector has now announced better business results and willingness to invest. A trend toward the production of high-efficiency solar cell structures and rising quality standards is evident. Fraunhofer ISE is well prepared to promote this trend with its research and to support the industry with R&D work and new concepts.

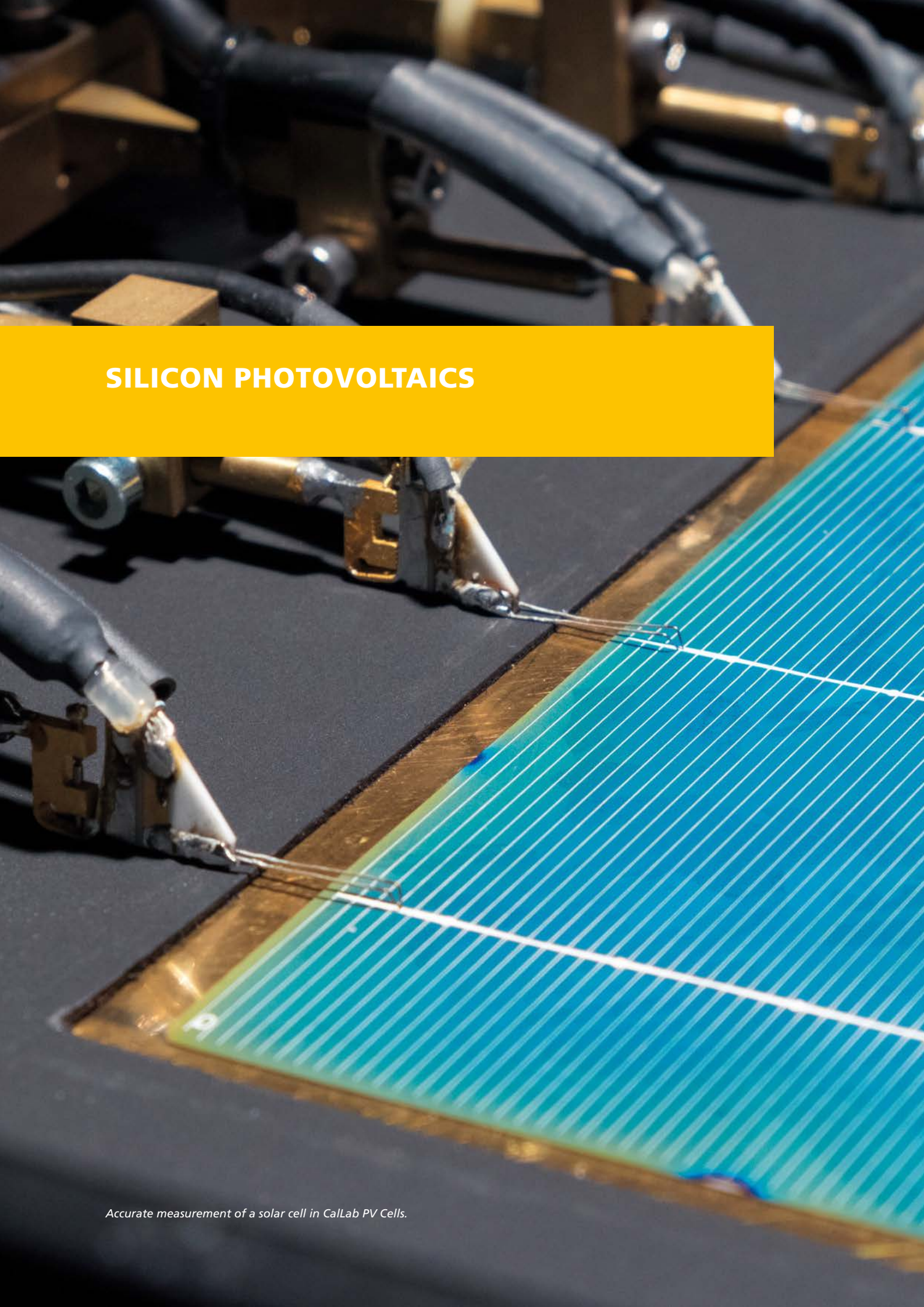
Photovoltaic R&D at Fraunhofer ISE has a focus on silicon photovoltaics (page 18). Accounting for more than 90 % of the global photovoltaic turnover, crystalline silicon continues to dominate the market. Despite the maturity of this technology, current developments are demonstrating that numerous innovations in this technological branch are feasible and also necessary to further reduce the price of a PV-generated kilowatt-hour. Current research at Fraunhofer ISE and its outposts in Freiberg, Gelsenkirchen and Halle addresses materials development, cell architecture, cell processing and production technology, module technology and testing, and quality control, to explicitly name a few examples. We cover technology readiness levels from demonstration of record-making solar cells to pilot processes and transfer to the industrial context. From materials to modules and up to the power plant scale in quality assurance, about 430 employees work on silicon photovoltaic technology at the Institute.

A further emphasis in photovoltaics at Fraunhofer ISE is on III-V and concentrator photovoltaics (page 26), in which 60 employees are involved. One of their goals is to further develop the extremely efficient solar cells based on III-V semiconductors. We proudly hold the current efficiency world record of 46 %. This type of multi-junction solar cell is applied in space or concentrator systems. In the latter technology, the incident light is first concentrated by an optical system and then directed onto the solar cell. In addition to the cell itself, we develop all further components required (optics, module, tracking controls, measurement technology) and investigate system-level issues.

The combination of Si and III-V expertise at Fraunhofer ISE is a unique feature and is used to develop silicon-based tandem solar cells: We have achieved a record efficiency value of more than 30 % for these devices, meaning that we have already exceeded the fundamental physical limit of 29.4 % for simple silicon-based solar cells. As an alternative to the combination with III-V, perovskites offer a further very interesting option for application in silicon-based tandem solar cells.

Finally, our research on photovoltaics also includes newly emerging technological topics and concepts for the future (page 30). In this field, Fraunhofer ISE is investigating technology such as organic, dye and perovskite solar cells. About 50 employees are working within emerging photovoltaic technology on concepts which will need significantly more than five years until they can be implemented industrially. Examples include up-conversion, down-conversion and photonic structures.

SILICON PHOTOVOLTAICS



Accurate measurement of a solar cell in CalLab PV Cells.

Interview with
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Prof. Stefan Glunz ✉ stefan.glunz@ise.fraunhofer.de

Total staff	**325**
Journal articles and contributions to books	**64**
Lectures and conference papers	**55**
Granted patents	**24**

www.ise.fraunhofer.de/silicon-photovoltaics

Which current technological trends should the German solar sector adopt?

Preu: Because of Asian dominance in mass production, we should focus on markets in which we have advantages. In photovoltaics, the efficiency value is decisive, being the central parameter in the levellized cost of electricity. The German solar sector is excellently prepared to develop next-generation, highly efficient solar cells and modules. In addition, production technology for highest-efficiency solar cells offers an important distinguishing feature for equipment manufacturers.

Where do you see the place for LFC technology, for which you, Dr Preu, and Dr Jan Nekarda received the Joseph von Fraunhofer Prize in 2016?

Preu: Laser-Fired Contact was the most accessible technology to structure the back surfaces of PERC solar cells. It enabled the industry to introduce it for multicrystalline silicon and smoothed the way for mass production. With LFC technology, it is now possible to produce the back electrode more efficiently and cost-effectively with aluminium foil instead of powder containing aluminium. We are currently cooperating with partners to develop a first industrially relevant prototype.

The 30th anniversary of "CalLab PV Cells" was celebrated in 2016. What services does the laboratory offer?

Glunz: Accurate calibration of solar cells is a service which is offered by only a few laboratories throughout the world, so it was always in strong demand. Since 1986, extremely accurately measured reference solar cells have been sent from Freiburg to destinations around the world. Manufacturers and researchers are thus able to make performance data truly comparable to each other. Today, 30 members of staff calibrate about 2500 solar cells and 5000 solar modules each year.

In 2016, you also celebrated the 10th anniversary of PV-TEC and the official opening of PV-TEC Select. Which milestones have been reached and what is still planned?

Preu: Due to further development of cell technology, both internationally and in PV-TEC, we have been able to improve our top efficiency values from 15.5 % in 2006 to 21.4 % in 2016. 40 Ph.D. theses were based on work in PV-TEC and more than 500 000 wafers were processed. PV-TEC Select is a further development for highest-efficiency solar cells with passivated contacts. For example, we have already achieved very good results with our TOPCon technology on a laboratory scale, with efficiency values exceeding 25 %. We intend to implement this type of cell technology in PV-TEC Select on a pilot-line scale. Front-end processing of solar cells, which is particularly sensitive to contamination, will be carried out here. Back-end processing, i.e. metallization, will continue to be done in PV-TEC.

Fraunhofer ISE also works on the characterization and quality assurance of the materials used. What are the new approaches here?

Glunz: The production of Si materials and solar cells is becoming increasingly professional. As in microelectronics, the demand for conclusive measurement methods and instruments is growing. We serve this market niche, among other products, with "modulum", our luminescence-based equipment, which can determine the electrical quality of silicon ingots, wafers and cells accurately. In addition to high-quality measurement technology, the sophisticated evaluation routines offer great added R&D value. We can adapt the "modulum" tool exactly to the specifications of users in photovoltaics.

Various Si-based tandem solar cell concepts are expected to achieve higher efficiency values than conventional solar cells. Which approaches are particularly promising?

Glunz: We are pursuing the combination of silicon solar cells both with perovskites and with III-V semiconductors. Very efficient tandem solar cells can already be produced with the well-established III-V semiconductors, so that we have achieved efficiency values exceeding 30 %. Perovskite-silicon tandem solar cells could offer the advantage of lower production costs, if they can be implemented successfully. Both development strands are very important for us, as silicon-based tandem cells offer the chance to continue the sucessful development of silicon photovoltaics.

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SELECTED R&D PROJECTS IN 2016

- Cost-optimized high-efficiency solar cells of low-oxygen n-type monocrystalline silicon
- High-throughput silicon-based films and silicon epitaxy
- Development of highly efficient and cost-effective silicon wafers
- Plated contacts – on the way to large-scale implementation
- Cost-beneficial aluminium metallization
- Prevention of light-induced degradation in solar cells via ultrafast regeneration
- Overcoming fundamental bottlenecks to a new world-record silicon solar cell
- Material- and process variations in multicrystalline PERC solar cells
- modulum – novel characterization tool

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/1-01

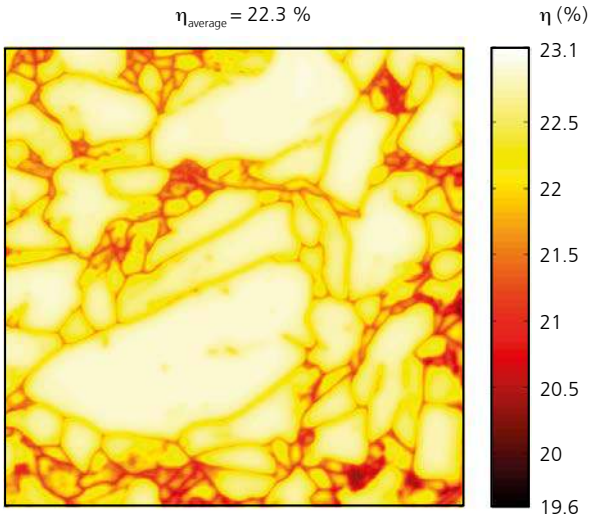
New materials / processes
Measurement-based analysis / quality control

MULTICRYSTALLINE N-TYPE SILICON FOR SOLAR CELLS

The combination of highly efficient solar cell structures and high-performance multicrystalline silicon (HP mc-Si) with very few dislocations makes it feasible to achieve efficiency values exceeding 20 %. HP multicrystalline silicon is characterized by the suppression of dislocation formation in the silicon and the use of crucible systems which reduce the incorporation of impurities. In the HP mc-Si that has been produced at Fraunhofer ISE, we achieved charge carrier lifetimes within grains that were significantly longer than 1 ms. These values are comparable to those of high-quality monocrystalline silicon, so that the electrical material quality is mainly limited by the recombination properties of the remaining grain boundaries.

We have developed n-type HP mc-Si doped with phosphorus, which has been adapted to the application in a TOPCon solar cell. By using an extremely pure silicon granulate as the seeding layer, we adjusted the grain structure of the crystal such that the proportional area of material zones that were limited by dislocations was less than 1 % through the entire height of the block. The photo shows a cross-section with dimensions of 420 mm x 220 mm through a G2-sized research block, with the granular seeding material at the lower edge of the block and the typical grain structure for HP mc-Si.

After the wafers produced from this block had been subjected to the boron diffusion required for the solar cell emitter, the lifetimes averaged over the entire wafer have values of approximately 400 µs. The first TOPCon solar cells, which were produced with a simplified process from n-type HP mc-Si originating from an initial development phase with lower material quality, already achieved an efficiency value of 19.6 % with an open circuit voltage of 663.7 mV. The ELBA method allows realistic estimation of the solar cell efficiency which can be achieved with the currently available material. The graph shows a 6 x 6 cm^2 detail from an n-type HP mc-Si wafer from the upper region of the block. The color code indicates the locally achievable cell efficiency. The efficiency values were determined for a further developed solar cell process with an adapted texture, which makes a maximum efficiency value of 23.1 % without material-dependent losses feasible. In the investigated material, it is no longer the grains themselves but the grain boundaries which impose limits, such that solar cell efficiency values exceeding 22 % over a large area can be expected. This work was supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the "THESSO" project.



Expected efficiency of the current silicon material in a TOPCon solar cell that has been adapted for mc-Si.

1 *Cross-section through an n-type high-performance multicrystalline silicon block with the seeding granulate at the base.*

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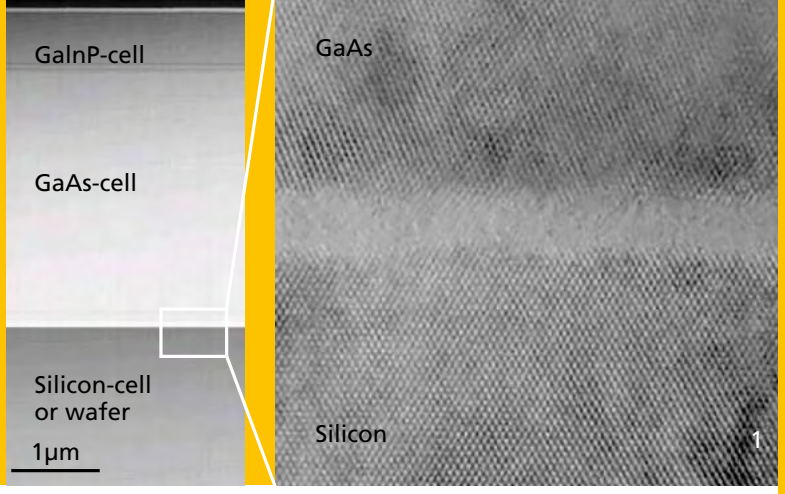


BEYOND THE AUGER LIMIT – SILICON-BASED TANDEM SOLAR CELLS

During the last decade, the efficiency value of silicon solar cells has approached the maximum achievable limit of 29.4 %, the so-called Auger limit, more and more closely. Efficiency values exceeding 22 %, which were feasible only with laboratory solar cells ten years ago, can be achieved today with industrially produced cell structures, whereas cell prototypes already reach values above 26 %. For the next ten years, there is still sufficient potential to increase the efficiency of traditional solar cells. However, in the longer term, novel cell architecture is needed to continue the technological development and thus further reduce the costs of photovoltaically generated electricity. One promising option is presented by silicon-based tandem solar cells, as they can build on the existing large-scale and cost-effective production technology for silicon solar cells. In this approach, the silicon solar cell is combined with a solar cell that has a larger band gap to better exploit the broadband spectrum of solar radiation. Perovskites or III-V semiconductors are particularly suitable candidates.

The combination of silicon with III-V semiconductors is an especially attractive variant for Fraunhofer ISE, as we can draw on many years of technological and scientific experience with both types of technology, which have resulted in many world records and industrially applicable production techniques.

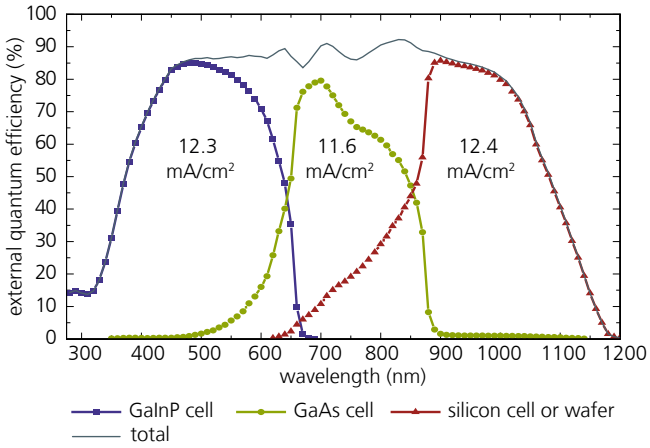
During the development of tandem solar cells based purely on III-V semiconductors, it became evident that only monolithic cell structures, in which all sub-cells form a compact semiconductor component, have real commercial potential, whereas other structures did not progress beyond the demonstration phase. Therefore, we have decided to follow this processing route also for silicon-based tandem cells, among other reasons because monolithic multi-junction solar cells with their normal contact structure on both surfaces can be connected to form modules in the same way as from conventional silicon solar cells.

As silicon and the III-V semiconductors used have different lattice constants, a monolithic configuration presents a major challenge. If epitaxy is applied to grow III-V layers directly on silicon, special buffer layers must be introduced to prevent crystalline defects in the III-V semiconductor. Alternatively, the two semiconductors can be joined together by wafer bonding. In wafer bonding, the silicon and III-V sub-cells are pressed together after special surface treatment and bond inseparably to form a single component. A thin amorphous semiconductor layer is formed during this process which, however, does not disturb the device properties (Fig. 1).

1 *Transmission electron micrograph of the III-V-silicon multi-junction solar cell. Whereas the complete thickness of the GaInP and GaAs sub-cells is shown, only the upper part of the approximately 200 µm thick silicon solar cell is visible. At higher magnification (right), the 4 nm thick amorphous layer that is created by the wafer bonding process is visible. The TEM image was recorded at the Christian Albrecht University of Kiel in the research group of Prof. Jäger.*

In order to cover the solar spectrum well, we have chosen a high-efficiency silicon solar cell and GaAs and GaInP solar cells as the components of our multi-junction solar cell. The three corresponding band gaps of 1.12 eV, 1.43 eV and 1.90 eV complement each other optimally and should permit efficiency values exceeding 30 %. Apart from the band gaps, in designing the cell architecture it was essential to ensure that the current densities in all three sub-cells have the same value, as the smallest current from one cell in the series connection of a monolithic structure determines the value of the total current. By contrast, the three sub-cell voltages add to give the new total voltage.

As demonstrated by the quantum efficiency measurement of the multi-junction solar cell produced at Fraunhofer ISE, this approach has succeeded well. Between them, the three sub-cells cover the spectral range between 300 nm and 1200 nm and their individual currents are very similar. The total voltage of the multi-junction solar cell is about 3.05 V. The calibrated measurement of our silicon-based tandem solar cell resulted in a record efficiency value of 30.2 % for non-concentrated solar radiation (AM 1.5g). This efficiency value represents a historic milestone in the development of solar cells. It is the first time that a silicon-based solar cell with a monolithically integrated structure has achieved an efficiency value that exceeds the Auger limit of 29.4 %.



Quantum efficiency measurement of the GaInP/GaAs/Si multi-junction solar cell. The grey line represents the sum of the partial currents from the GaInP (blue), GaAs (green) and silicon (red) solar cells.

2 *4 cm² large GaInP/GaAs/Si multi-junction solar cell for applications under non-concentrated solar radiation. Due to the monolithic configuration, the solar cell can be contacted on the front and back surfaces, in the same way as conventional solar cells.*

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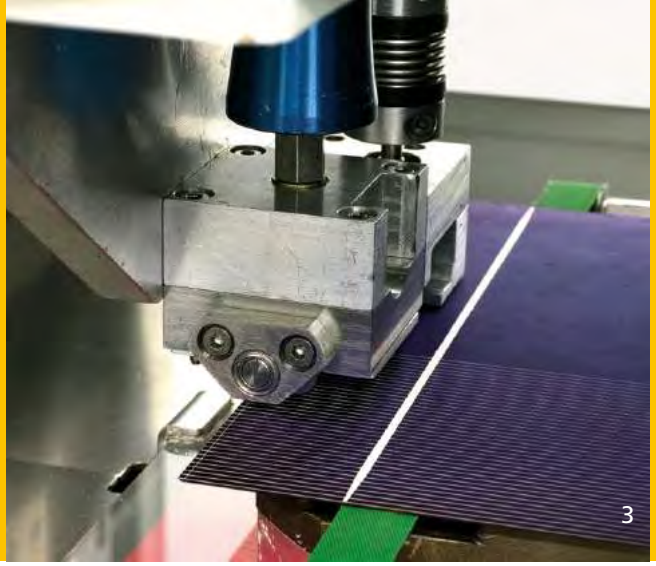
10TH ANNIVERSARY OF PV-TEC AND OFFICIAL OPENING OF PV-TEC SELECT

Opened early in 2006 as the Research Factory for Solar Cells, the Photovoltaic Technology Evaluation Center PV-TEC at Fraunhofer ISE was the first institute-based pilot line for crystalline silicon solar cells. With the support of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU), the new, unique laboratory with a floor area of 1200 m^2 offered research, development and service on a production scale to the photovoltaic industry. This accelerated technological transfer to industry enormously. PV-TEC functioned as a pilot for Germany's ascent to becoming the international leader in solar cell production and manufacturing technology, a position it still holds today in manufacturing technology.

The advisory board, consisting mainly of industrial representatives, has supported the demand-relevant further development of our large-scale laboratory since its foundation. The goal of PV-TEC in 2006 was not only to reduce the cost of solar electricity, but also to provide quality assurance for efficient PV research and development, and thereby support and strengthen the German and European PV industry. Since then, we have characterized and processed more than 500,000 silicon wafers and carried out more than 4000 experiments on large-scale equipment. Education and training also had and still have high priority. To date, more than 40 Ph.D. theses have been written on the basis of technological and metrological/analytical work in PV-TEC.

Although PV-TEC was initially designed for the classic solar cell with screen-printed contacts, German Federal and State support allowed the technological facilities to be expanded to accommodate more recent solar cell structures with passivated surfaces. This contributed to us increasing the record efficiency value for industrially relevant solar cells from 15.5 % to 21.4 % now in PV-TEC. Both back-contact and bifacial solar cell types are produced and characterized. For these types of solar cells, we have developed industrially relevant processing routines which reduce the additional processing effort to a minimum, e.g. by simultaneous doping with different materials (co-diffusion). Within the "RDemo" project, modules with so-called HIP-MWT solar cells, back-contact solar cells produced in PV-TEC, were successfully integrated into the façade of a new building at Fraunhofer ISE.

Altogether, over the past ten years, the laboratory has contributed significantly to the introduction of new cell concepts and production technology to industrial production. In particular, the introduction of a laser-structuring technique to produce local point contacts on the back cell surface, which met the requirements for high throughput, was essential and was recognized in 2016 with the Joseph von Fraunhofer Prize. Other outstanding milestones in the transfer of new production technology to an industrial context were the development of back-surface passivation layers based on aluminium oxide layers deposited by PECVD processes and the development of the multiple-jet dispensing procedure to create extremely fine contacts (< 30 µm) with high aspect ratios.



The technological developments were accompanied by comprehensive developments in metrology and analysis, which allowed novel cell structures such as back-contact cells or bifacial cells to be measured automatically, integration of imaging measurement techniques such as luminescence measurement into production lines and fully automatic analysis of the resulting data. Prominent results include luminescence-based methods for quantitative, spatially resolved analysis of solar cells, a procedure based on machine learning to evaluate the material quality of multicrystalline wafers in their raw sawn state and a simulation-supported procedure to analyze process fluctuations.

Together with the anniversary of the first solar cell pilot line in a research environment, the official opening of the PV-TEC Select laboratory extension was also celebrated on 13th April, 2016. This is a new pilot center with a clean-room laboratory area of 800 m² for "front-end processing", which designates solar cell processing before metallization. This enables us to develop highest-efficiency solar cells based on selective contacts in an industrially relevant environment and to strive for efficiency values up to 25 %. Both established technology, such as heterojunction technology based on thin amorphous silicon layers, and technology developed at Fraunhofer ISE, such as TOPCon technology and thin-film stacks based on polycrystalline silicon, are applied here. Industry thus has access to a unique option to evaluate suitable processing equipment on a pilot scale in surroundings comparable to a clean room.

PV-TEC Select in Freiburg is located in the immediate vicinity of RENA, a producer of manufacturing facilities and equipment. This allows synergetic effects in the usage of wet-chemical processing systems. Further space and potential for facilities from other industrial partners are available. The fundamental idea of PV-TEC, creation of a pool of basic technological components for the development of new generations of solar cell technology, is thereby extended further. In close cooperation with industrial partners and applying hetero-junction technology, solar cell efficiency values of 22 % were obtained in PV-TEC Select soon after the new laboratory area had been opened. PV-TEC Select was supported by the State of Baden-Württemberg via its Ministry for the Environment with regard to infrastructure and premises, and by the German Federal Ministry for Economic Affairs and Energy (BMWi), which provided investment funding for equipment.

1 *In PV-TEC, production-scale equipment is available to develop industrially relevant processing sequences.*
2 *Industrial tubular furnace for boron diffusion and co-diffusion processes to produce n-type silicon solar cells in PV-TEC.*
3 *Dispensing robot with ten jets for the multiple-jet dispensing procedure to create extremely fine contacts that was developed at Fraunhofer ISE.*

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III-V AND CONCENTRATOR PHOTOVOLTAICS

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Total staff	**59**
Journal articles and contributions to books	**20**
Lectures and conference papers	**27**
Granted patents	**4**

www.ise.fraunhofer.de/iii-v-and-concentrator-pv

Under this research topic, we address the demands which arise in the space and terrestrial concentrator photovoltaic markets. Today, satellites are equipped almost exclusively with highly efficient III-V multi-junction solar cells. For this market, we are developing lighter and more efficient solar cells of the next generation, which better withstand bombardment by high-energy electrons and protons. High efficiency values and low costs are also demanded in applications of III-V multi-junction solar cells in highly concentrating photovoltaic systems on earth.

One focus of our work is the development of four-junction solar cells, which can achieve efficiency values of 50 % in concentrator applications and 36 % in space. We are investigating a wide range of cell architectures and applying concepts such as metamorphic growth and/or direct semiconductor bonding. This allows us to combine different semiconductors such as GaSb, GaAs, InP, Si or Ge. Last year, a three-junction solar cell of GaInP/GaAs//Si with an efficiency value exceeding 30 % under non-concentrated sunlight was demonstrated for the first time (page 29). This technology opens new options for highest-efficiency flat PV-modules.

We also are investigating a special application of III-V photovoltaic cells: illumination with monochromatic illumination from LED or laser. Here, very high conversion efficiency values of up to 60 % can be achieved.

III-V multi-junction solar cells are used terrestrially in highly concentrating photovoltaic systems. Fraunhofer ISE has achieved a world record efficiency value of 46 % for converting solar radiation to electricity with this type of solar cell. For this application, we design, investigate and test optical components that concentrate sunlight by factors between 300 and 1000, before it is converted into electricity by the III-V multi-junction solar cell. The lens-based FLATCON® module that we developed is a good example. We are continuing to optimize it to achieve higher efficiency values and lower production costs. In our ConTEC (Concentrator Technology and Evaluation Center), we investigate module production processes and the reliability of different module concepts. Our competence in thermal, optical and electrical simulation is available to interested clients.

In addition to highly concentrating photovoltaics based on III-V multi-junction solar cells, we are also working on low-concentration systems. These cover the concentration range up to factors of 30. Here, we offer cooperation with our clients in the development of optical concentrators and photovoltaic receivers, as well as in the design and measurement of systems. We have developed special silicon solar cells for application in low-concentration systems. In PV-TEC (Photovoltaic Technology Evaluation Center), series can also be produced for individual, client-specific applications.

Test rig for electronic characterization of a CPV mini-module on the outdoor test stand of Fraunhofer ISE. The mini-module achieved a world-record efficiency value of 43.3 % under concentrator standard test conditions (CSTC).

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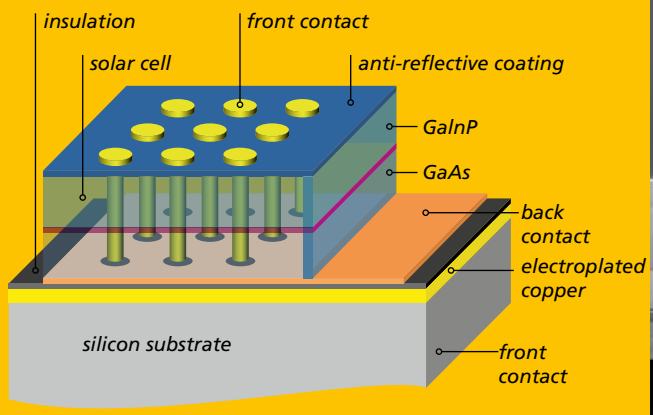
SELECTED PROJECTS IN 2016

- High-efficiency III-V multi-junction solar cells on silicon
- Extremely thin cells on metal foil with recyclable substrates
- CPV-T system combined with desalination systems
- Highly efficient concentrator module with GaSb-based four-junction solar cell
- Research cooperation on innovative climate technology – CPV India
- Development of a standard to determine the rated power of CPV modules

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/1-02

New materials / processes
Prototypes / pilot series
Measurement-based analysis / quality control



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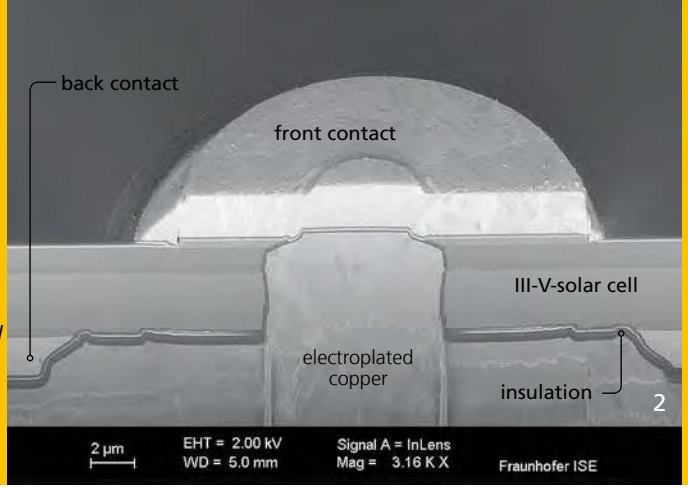

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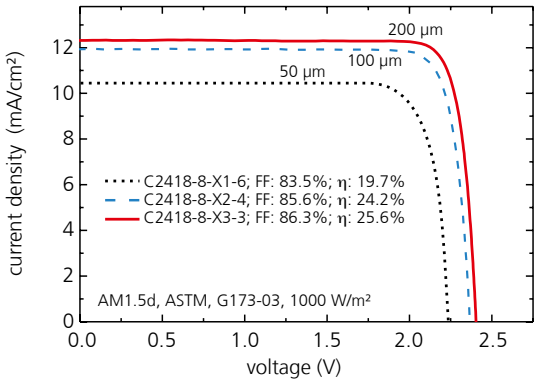
METAL-WRAP-THROUGH (MWT) III-V MULTI-JUNCTION SOLAR CELLS

Solar cells based on III-V semiconductor materials, when exposed to concentrated sunlight, achieve the highest efficiency values – up to 46 % – for photovoltaic energy conversion. For high concentration factors of more than 500 suns, the solar cell area is limited to only about 1 cm², as otherwise the losses resulting from shading and electrical resistance in the front contacts would be too large. One solution to these limiting problems is to relocate the contacts from the front to the back of the solar cell, such that these losses can be minimized. This approach is known as "Metal-Wrap-Through" (MWT) technology from silicon photovoltaics. The front contacts are led through electrically insulated holes, so-called "vias", through the solar cell layers, so that only small contact points are needed on the front surface of the solar cell. This minimizes shading, eliminates the need for electricity conduction through grid fingers on the front surface and allows the connection of several solar cells on the back surface.

This technologically demanding cell architecture was implemented in III-V solar cells for the first time in cooperation with the French research institute, CEA, in Grenoble, as part of the "VirtualLab" project. A simplified design was chosen, in which the front contact of the cell is led through to the back surface and the back contact is accessible from the front (Fig. 1). The scanning electron micrograph (SEM) of the cross-section of a via shows continuous insulation of the via wall, which is necessary for a functional cell (Fig. 2).

The distance between the vias must be chosen such that the current flowing to the via experiences only low electrical resistance but simultaneously shading is minimized. In order to test this experimentally, solar cells with different distances ("pitches") between the vias in a hexagonal pattern were produced and electrically characterized. The cells with the largest pitch of 200 µm produced the best results with an efficiency value of 25.6 %, when measured with an AM 1.5d solar spectrum (graph below). The shading caused by the contact points on the cell surface amounted to about 16 % / 4 % / 1 % for a pitch of 50 / 100 / 200 µm, respectively. At higher concentration factors, the efficiency value of the cells increased to 28.3 % at 176 suns and 27.2 % at 800 suns. The cell efficiency can be further increased, when a three-junction solar cell is used instead of a dual-junction solar cell and the via design is optimized.



IV characteristics and efficiency values (AM1.5d) of three MWT solar cells with different via pitches.

1 *Illustration of MWT architecture.*

2 *SEM image of the cross-section of a MWT cell with front and back contacts as well as the via formed by electroplated copper.*

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EMERGING PHOTOVOLTAIC TECHNOLOGY

Screen-printed electrode for development of perovskite solar modules.

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Total staff	**53**
Journal articles and contributions to books	**9**
Lectures and conference papers	**8**

www.ise.fraunhofer.de/emerging-pv-technologies

Emerging Photovoltaic Technology encompasses dye and perovskite solar cells, organic solar cells, photon management and tandem solar cells on crystalline silicon. The aim is to evaluate optimization potentials in photovoltaics with the help of these novel technologies and to reduce the levelized cost of electricity. This includes improving the efficiency of well-established solar cells, e.g. of crystalline silicon, by improving the absorptive and reflective properties via advanced photon management. Another approach is provided by alternative processes and materials such as dye and organic solar cells, which – although their efficiency is somewhat lower – offer clear potential for cost reduction.

We are conducting basic research on organic solar cells, particularly addressing the fundamental properties of selective contacts and their implementation with inexpensive, durable raw materials and extremely thin films. In addition, we aim to transfer promising results from the cell level to the module level with the goal of realizing cost-efficient, flexible and durable organic solar modules. Our overall aim is to cooperate with industrial partners in developing stable coating and encapsulation processes on our roll-to-roll coater which can then be used in full-scale equipment.

Perovskite solar cells also consist of very inexpensive raw materials and can be produced in low-temperature processes, similar to organic solar cells. However, the properties of the crystalline perovskite absorber layers and the very high efficiency values already achieved make them more similar to crystalline inorganic solar cells. In order to realize adequate long-term stability, we draw particularly on the experience we have gained in upscaling dye solar modules based on glass-glass configurations. In our research on perovskite and organic solar cells, we cooperate closely with the Freiburg Materials Research Centre (FMF) at the University of Freiburg.

We are developing silicon-based tandem solar cells to make better use of the solar spectrum by reducing thermalization losses. In addition to adapting the processes for the Si bottom cell and developing tunnel contacts, we are also working on new silicon nano-crystalline materials with adjustable band gaps and III-V-based absorber materials. The two single sub-cells are combined either by growing the top cell epitaxially directly on the bottom cell, or by wafer bonding. A further focus of our work is the development of perovskite and silicon layers for highly efficient perovskite-silicon tandem solar cells. In doing so, we specifically apply our photon management concepts to ensure good current matching between the sub-cells.

In the area of photon management, we develop concepts, materials and technology to increase the efficiency of conventional photovoltaic technology by applying optical approaches. These include light-trapping structures such as diffractive gratings and scatterers, up-conversion, angular selectivity and spectral splitting. The investigated concepts are usually not restricted to a specific solar cell technology.

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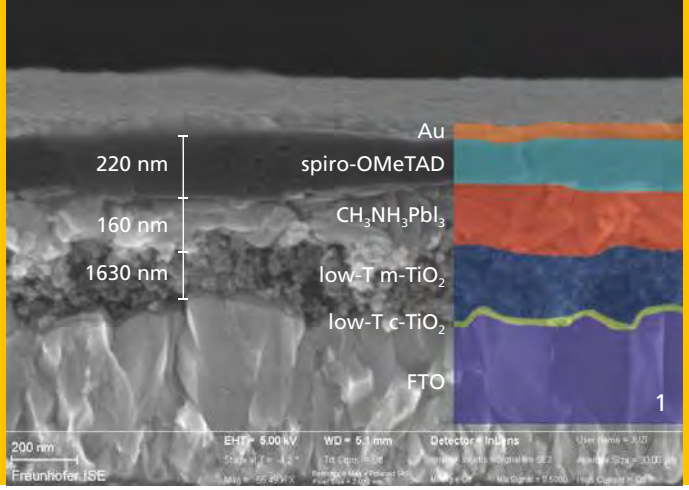
SELECTED PROJECTS IN 2016

- Scalable perovskite technology
- Perovskite-silicon tandem solar cells
- Nano-structures for luminescence amplification to increase the efficiency value of LEDs and solar cells

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/1-03

New materials / processes



LOW-TEMPERATURE ROUTE FOR PEROVSKITE SOLAR CELLS

One of the central goals in our work on Emerging Photovoltaic Technology is to develop highly efficient silicon-perovskite tandem solar cells based on a combination of a crystalline silicon bottom cell and a perovskite top cell. In order that a c-Si / a-Si heterojunction solar cell can be used as the bottom cell, high-temperature steps must be avoided in the subsequent processing.

However, the highest efficiency values for perovskite solar cells have been obtained to date by inclusion of two TiO_2 layers, one compact, the other nano-porous, which are tempered at temperatures of around 500 °C. To allow titanium dioxide still to be used, a low-temperature route was explored and developed further. In it, the compact TiO_2 layer is not produced as usual by spray pyrolysis, but by evaporation under high vacuum. The nano-porous TiO_2 layer is treated at low temperatures with UV radiation of a suitable wavelength. These alternative processes are completely compatible with the usage of a c-Si/a-Si heterojunction solar cell as the bottom cell. The efficiency values of the perovskite solar cells, which were produced by applying the described low-temperature route, are promising, with values of up to 16 % being achieved. The corresponding layer stack is glass/F:SnO_2/TiO_2 (compact)/TiO_2 (nano-porous)/perovskite absorber ($CH_3NH_3PbI_3$)/spiro-OMeTAD/gold, as illustrated in Fig. 1.

In future, we aim to develop this approach further, improve the quality of the perovskite absorber layer and replace the organic hole conductor, spiro-OMeTAD, with alternative materials in combination with a metal grid as the top electrode. Furthermore, the band gap of the perovskite absorber should be increased to approach the optimal value of 1.75 eV for combination with crystalline silicon.

A further point being addressed is reduction of the hysteresis caused by migration of ions and ion vacancies. To do this, we have selected an approach which combines experiments to implement highly selective contacts, their detailed characterization and numerical simulation, in order to understand the underlying principles still better and describe them quantitatively.

1 *Scanning electron micrograph (cross-section) of a perovskite solar cell produced with a low-temperature (< 150 °C) processing route.*

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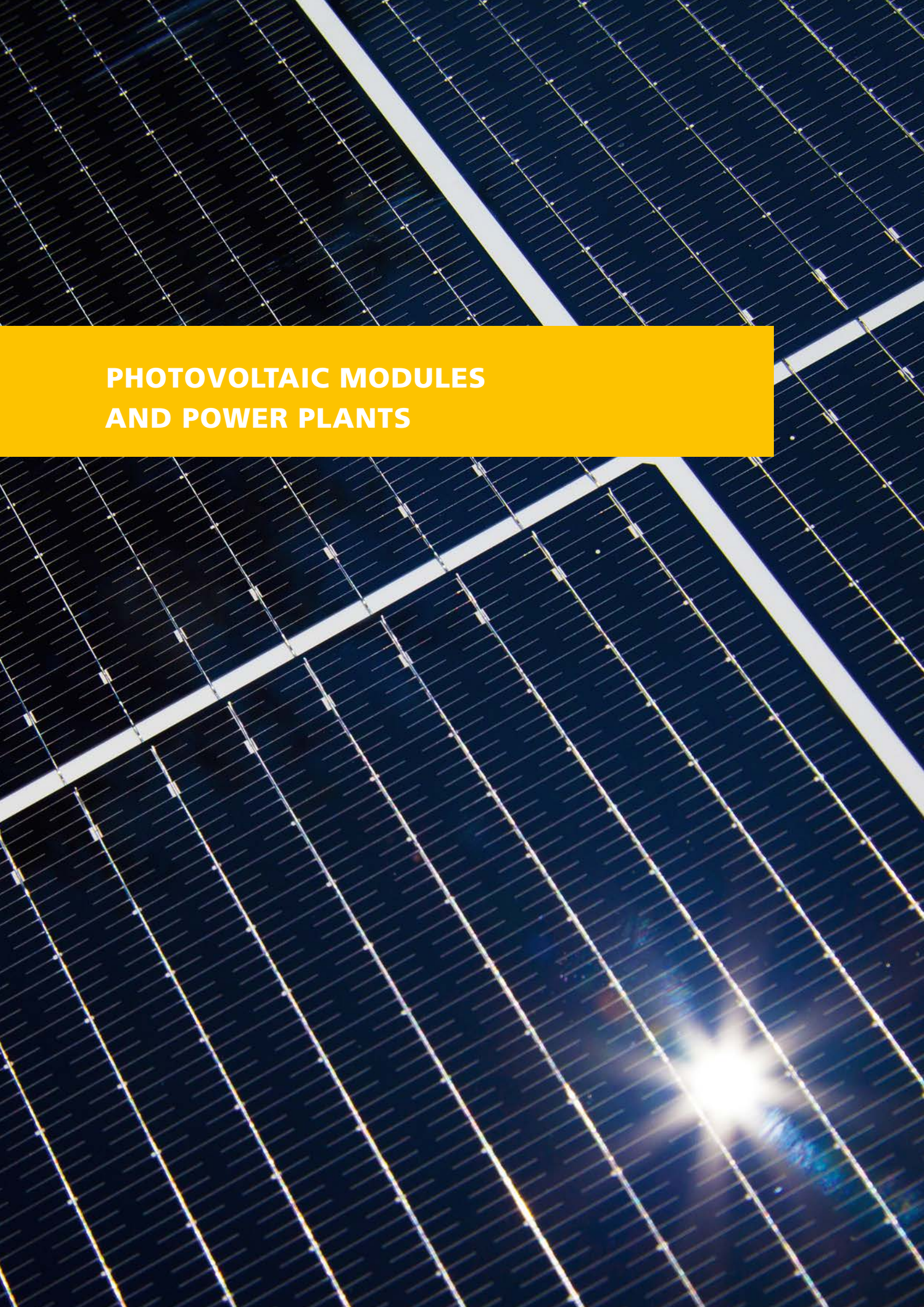
PHOTOVOLTAIC MODULES AND POWER PLANTS



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Total staff	**104**
Journal articles and contributions to books	**9**
Lectures and conference papers	**14**
Granted patents	**8**

www.ise.fraunhofer.de/pv-modules-and-power-plants

Module technology converts solar cells into durable products for safe operation in PV power plants. Fraunhofer ISE supports the development of PV modules from solar cells with respect to optimal efficiency, reduced costs, enhanced reliability and special applications such as building integration. We characterize modules at the highest level of accuracy, test them comprehensively and analyze their service lifetime. From the planning process through to long-term operation, we offer quality-control and performance-optimizing services for PV power plants.

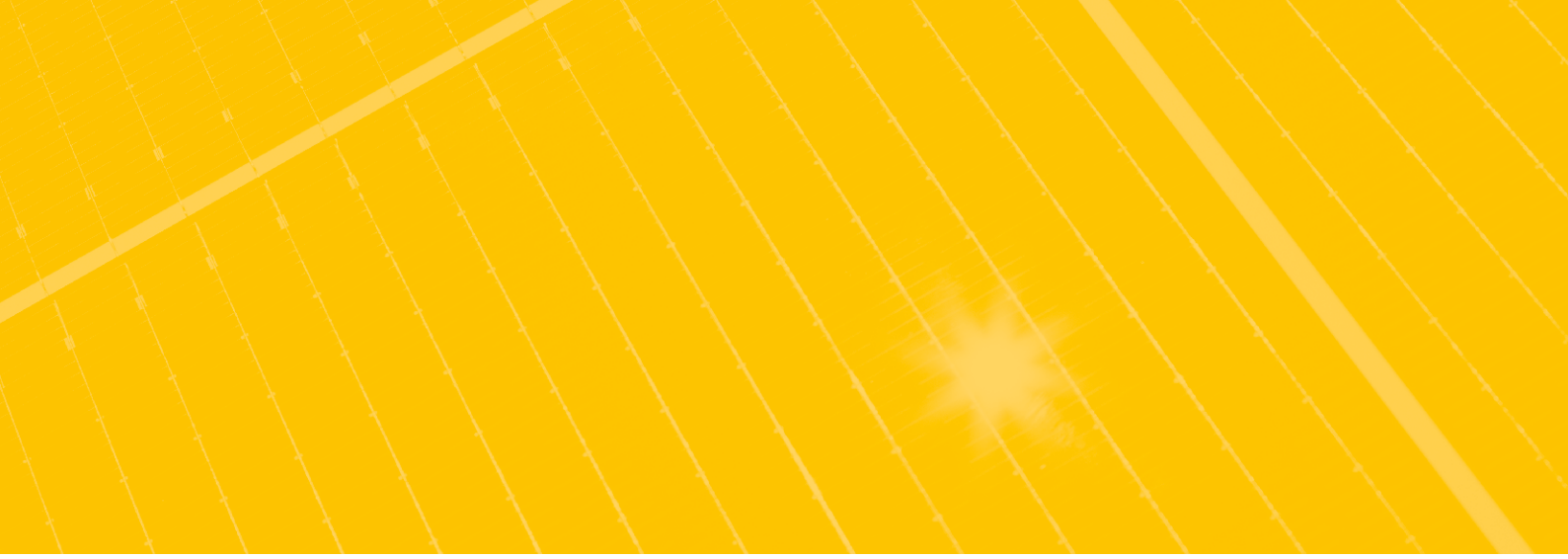
The Photovoltaic Module Technology Center (Module-TEC) is equipped with a wide range of modern processing and analytical platforms for connecting and laminating solar cells, for material testing, as well as for product and process development. We apply measurement and simulation to analyze cell-to-module balances (CTM), produce module prototypes and transfer developments from the laboratory directly to module pilot production in relevant module batches and formats. We develop customized solar modules for special applications (integration into façades, vehicles and devices).

The lifetime and degradation behavior of components in a PV power plant are decisive in determining its profitability. We monitor PV modules under different climatic conditions with equipment that has been developed in house. Degradation monitoring and failure analysis help us to understand aging mechanisms and identify them as early as possible. We develop simulation models and accelerated testing procedures to investigate aging behavior, particularly to characterize new materials and components. Not only the equipment of our 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. Highest accuracy is also offered by our accredited calibration laboratory. CalLab PV Modules, which is one of the internationally leading laboratories in this field, achieves a measurement accuracy of better than 1.6 % for crystalline modules.

With the five phases of the Fraunhofer ISE quality cycle – development, engineering, procurement, commissioning and operation – we guarantee comprehensive quality control of PV power plant projects. We take site-specific and climatic factors into account to prepare accurate yield predictions and provide advice on the project-specific selection of high-quality components. Comprehensive quality testing after commissioning provides an independent assessment of performance, among other benefits. Our procedures have been proven internationally and are recognized by banks, insurance companies and investors. We develop reliable, probabilistic methods for short-term power forecasting of PV systems.

Based on our expertise in photovoltaics and energy supplies for buildings, we investigate topics concerning the integration of photovoltaics into the building envelope. Not only energy-relevant and architectural aspects but also building science and structural requirements are taken into account.

Detail of a solar module with multi-wire connection of crystalline silicon solar cells. This connection technology reduces silver consumption and resistance losses, while improving the optical conversion efficiency in the module.



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SELECTED PROJECTS IN 2016

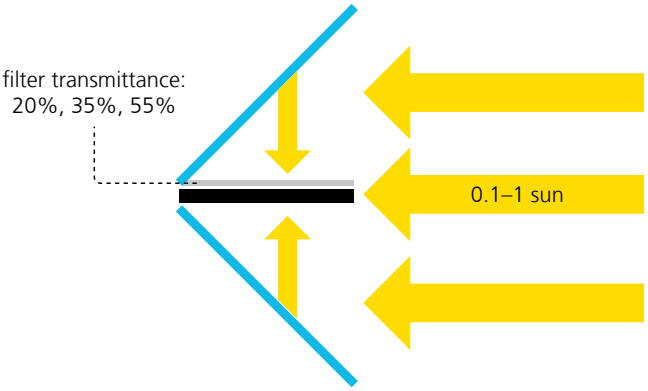
- Mosaic modules as photovoltaic design elements for solar façades
- BIPV on a laboratory building
- Improving module performance by analysis of cell-to-module losses with SmartCalc.CTM
- Global load classification system for solar-technical materials
- Development of characterization methodology for modules and systems applying bifacial PV technology
- BIPV system design for Art Nouveau building

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/1-04

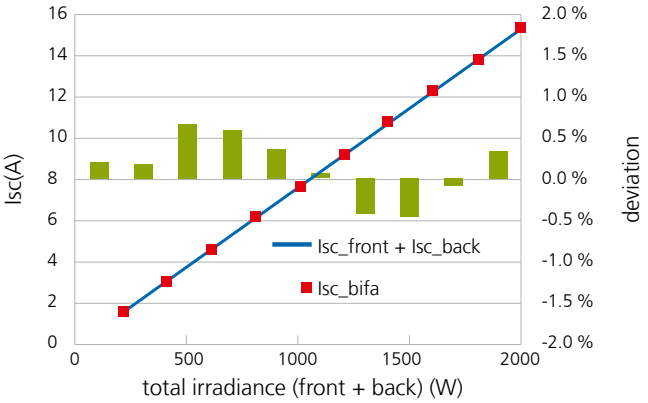
Prototype / pilot series
Software / application
Measurement-based analysis / quality control
Consultancy / planning / studies

NEW TEST STAND TO CHARACTERIZE BIFACIAL PV MODULES

Bifacial PV modules are able to convert light that is incident on either the front or the back surface into electricity, and thus offer great potential to increase the yield of PV power plants. The additional yield of 5 to 20 % in comparison to conventional modules depends on the amount of back-surface irradiation and efficiency. However, bifacial modules introduce new demands on measurement procedures in the laboratory. To calibrate bifacial modules with radiation on both surfaces, we have developed and constructed a test rig in CalLab PV Modules, which allows the module to be illuminated from both sides with different irradiance levels and intensity ratios. The light of the precise flash lamp simulator is deflected via two mirrors mounted at an angle of 45° to each other onto the front and back of the bifacial module. Different irradiance levels can be set by the adjustable lamp power and the insertion of attenuating gratings into the light path to the back of the module. Typical irradiance ratios that can be expected in various geometrical configurations for installations can thereby be simulated. In this way, we determine a bifacial power rating, with results that can be used as inputs to yield calculations and simulations. With the newly developed test stand of CalLab PV Modules, bifacial PV modules with an area of up to 1 m x 2 m can be calibrated under defined illumination conditions on both surfaces for the first time. With our tools for module characterization and system simulation, we will be able to accurately evaluate and optimize future bifacial PV power stations from the single module, through the mounting system, to the geometrical configuration of the installation. Due to the comprehensive characterization and calibration of bifacial modules in the new test stand, they can be used as reference modules in the production line for precise rating of bifacial modules, appreciably reducing the measurement uncertainty for this technology. The new development by Fraunhofer ISE to calibrate bifacial PV modules surpasses the specifications for Class AAA solar simulators according to the IEC 60904-9 standard.



Measurement set-up with two mirrors at an angle of 45° to the lamp, with variable irradiance levels and intensity ratios.



Sum of short circuit current (Isc) from separate front and back irradiance compared to measured bifacial current (Isc_bifa) from equal bifacial irradiance.

1 *Bifacial module mounted in the new test stand.*

2 *Frameless bifacial PV module.*

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SOLAR THERMAL TECHNOLOGY

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Journal articles and contributions to books	**15**
Lectures and conference papers	**16**
Granted patents	**1**

www.ise.fraunhofer.de/solar-thermal-technology

For the transformation of our energy sytems in the heat sector, solar thermal energy is a central component alongside energy efficiency. The role of solar thermal energy in different national economies and climatic zones also depends on cost developments in production and distribution. Research and development can make a contribution by developing more cost-effective materials, manufacturing processes and optimized complete systems. Here, not only the investment needed but also the annual operating costs play a significant role.

In our work on Solar Thermal Technology, we are concerned with optics and surface technology to better transmit, reflect, absorb, redirect or concentrate solar radiation, depending on the application. Components and systems technology for solar-thermal applications are developed further in all aspects: Solar-thermal flat-plate and evacuated tubular collectors find diverse applications from domestic hot water and space-heating systems to coolers and chillers. Competition with photovoltaics for installation space means that new developments in thermal collectors combined with photovoltaic power generation are important. Façade integration applying new flat heat pipes offers design flexibility. Linear concentration allows operating temperatures from 150 °C up to 550 °C to be reached. In addition to applications in large power stations for solar-thermal electricity generation, it also offers an option with simpler and less expensive variants to generate process heat, processing steam and heat to drive absorption chillers.

Energy efficiency in industrial plants also represents an important application field for solar thermal technology. For example, we are working on improving the supply of heat by steam or other heat-transfer media, on storage units for high-temperature heat, or on increasing the efficiency of production processes with the help of innovative heat transfer. Membrane-based processes, driven by solar or waste heat, can be used to purify industrial waste water or to concentrate residual materials so that they can be recycled better.

Fraunhofer ISE possesses expertise in materials science, component design, characterization and testing procedures, theoretical modelling and simulation, systems control and systems technology for the different applications.

Prototype of a linear Fresnel collector for solar processing heat up to 250 °C, which was developed by the Soltigua company in cooperation with Fraunhofer ISE. We demonstrated our method for performance measurement under dynamic test conditions with this installation on one of our roofs.

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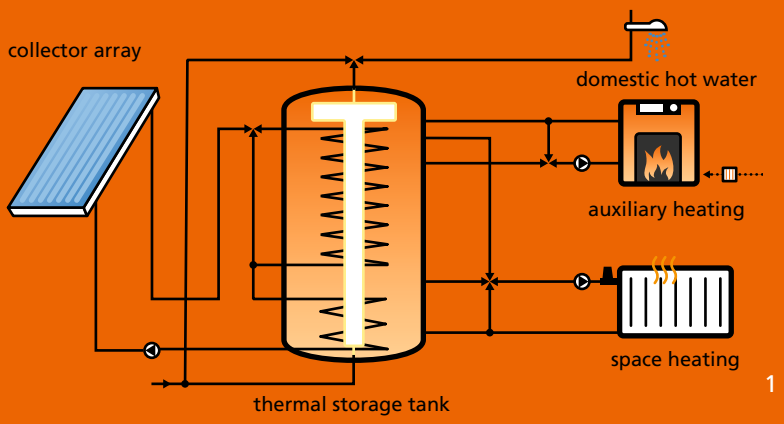
SELECTED PROJECTS IN 2016

- Development of novel technology for solar-thermal power towers
- Salt-based latent heat storage units for solar steam generation and use of waste heat
- Optimized PVT collectors for combined electricity and heat generation
- Development and measurement of novel solar air-heating collectors and investigation of suitable energy usage concepts
- Development of architecturally well-integrated façade collectors with heat pipes
- Service life estimation for solar-thermal collectors and their components
- Model-based analysis of measurement data from solar-active buildings
- Techno-economic optimization of combined solar-thermal systems
- Dissemination of innovative solar-thermal applications within Tunisian industry
- Standardization of yield analyses for solar thermal power plants
- Operating strategies for demand-responsive electricity generation by solar thermal power plants in the low power range

Further information on these and other projects:
www.ise.fraunhofer.de/en/research-projects/2-00

New materials / processes
Prototype / pilot series
Measurement-based analysis / quality control
Consultancy / planning / studies



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THE FUTURE OF SOLAR HEATING

The technology to use solar radiation to heat domestic hot water and provide space heating is reliable and well-established. The advantages are obvious: utilization of a free source of energy and almost emission-free provision of heat. Nevertheless, the European solar-thermal sector is suffering a crisis. The main reasons for this situation are the marked decrease in energy prices and the associated decline in public and political interest, on the one hand. On the other hand, other topics are currently dominating the political agenda, overshadowing the urgency of transforming our energy supply.

Despite this, it can be expected that solar heating will play a more important role in future. The fossil fuels of today will be depleted, even if it is difficult to predict exactly when this will happen. This will inevitably lead to strongly rising energy prices and stimulate the application of renewable energy sources. Which type of renewable technology will dominate in this context will be decided not only by the aspect of micro-economic competitiveness, but also by macroeconomic cost evaluation, social acceptance and the political will to promote certain technological options.

It is essential for the success of solar-thermal heating systems to reduce the system costs for the user. When the entire process chain is examined, it becomes apparent that significant costs are incurred beyond the actual manufacturing processes for the components. Thus, approaches are important which do not only address cost optimization of the components. Fraunhofer ISE is contributing to the "TEWISOL" project by developing methodology to analyze the complete process chain. The aim is to investigate and optimize value creation from product development through the manufacturing processes for components and systems, to system commissioning and installation by craftsmen. The results will indicate which technical simplification and standardization of components and systems, which changes in the process chain and which product complexity correspond to the expectations of the market and simultaneously offer maximal cost advantages.

Solar heating systems, which provide most of the heat needed for space heating and domestic hot water, can make a significant contribution to the success of the energy transformation. Fraunhofer ISE has successfully investigated this type of heating system in the "HEIZSOLAR" project. These systems present an essential option for fulfilling the nearly-zero energy requirements on buildings that will be demanded in future and are defined by the EPBD (Energy Performance of Buildings Directive) of the EU. In contrast to electricity-based heating systems, such concepts reduce the load on the electricity grid. This in turn can mitigate the problem of lacking acceptance for the necessary accelerated expansion of the electricity grid.

1 *Schematic system diagram of a solar-thermal system for space heating and domestic hot water.*

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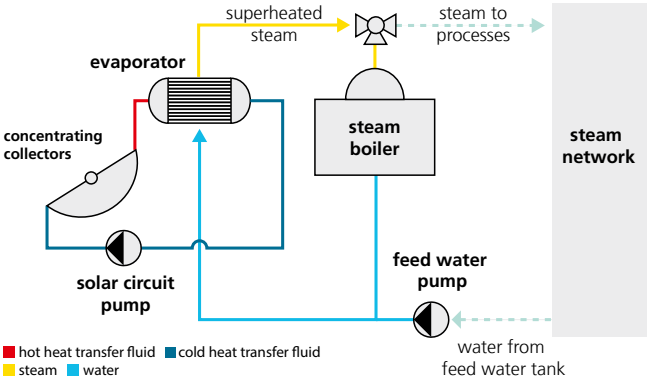
INTEGRATING SOLAR PROCESS HEAT INTO THE FOOD AND BEVERAGE INDUSTRY

Heat for industrial processes is responsible for a major portion of the world's end energy consumption. Residential buildings and transport consume similar amounts and exceed the end energy consumption for electricity generation by 20 %. When the contribution of solar-thermal technology to supply the heat requirements of industry is considered, the close relationship between process temperature and solar technology is important. Low-temperature and medium-temperature technologies such as stationary collectors or linearly focusing concentrators are commercially available today and suit the process requirements found in the sectors that are not energy-intensive, which are responsible for 48 % of the end energy consumption in industry. Among these, the food and beverage sector is the most relevant, with typical process temperatures in the range from 20 °C to 220 °C. Fraunhofer ISE is thus taking this sector as an example in its investigations on the usage of solar heat.

The food and beverage industry is the most important industrial sector in Tunisia, representing about 22 % of the total national industrial output. Furthermore, Tunisia is a country with high solar radiation totals. Due to these advantageous conditions for the economic application of solar heat, Fraunhofer ISE was commissioned by GIZ to conduct a study on the integration of solar process heat into the food & beverage sector. Possible strategies and the potential for waste heat recovery strategies and energy efficiency measures were studied, taking a yeast manufacturer, a dairy and a brewery as examples.

Energy-efficiency measures such as pre-heating the boiler feed water with boiler exhaust gases, pre-heating the air for boiler combustion with waste air from the compressor or pre-heating the air for drying facilities with exhaust air were considered. Concerning solar process heat, integration of solar heat at both the processing and the supply levels was studied.

Supply-level integration of direct or indirect solar steam generation was considered at a more detailed level.
Whereas the technical implementation of most measures would be feasible, the economic results show that there are still challenges to be overcome. Under current market conditions in Tunisia, energy-efficiency measures could attain payback periods of one to three years, whereas solar process heat still depends on public incentives to achieve payback periods of about five years. The foreseeable future cost increase for conventional fossil fuels will probably create a more favourable framework for solar process heat.
Fraunhofer ISE, with its capacity for techno-economic analysis and optimization, can support the integration of solar heat into industrial processes in future applications.



Hydraulic schematic diagram for indirectly solar-generated steam in supply-level integration.

1 *Measurements to analyze process heat at a yeast manufacturing company in Tunisia.*

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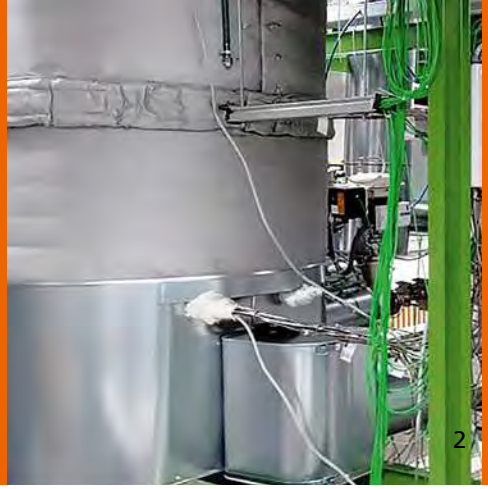
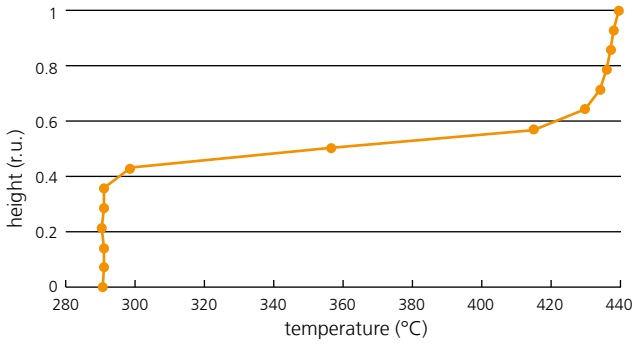


PROTOTYPE OF A SINGLE-TANK MOLTEN-SALT STORAGE UNIT

High-temperature storage units in solar-thermal power plants allow electricity generation to be decoupled from the availability of solar radiation, so that the electricity supply can respond to demand. This is a decisive advantage compared to wind energy and photovoltaic systems and an important feature in transmission grids with a large share of energy from renewable sources. Two-tank molten-salt storage systems are used for this purpose in existing solar-thermal power plants. A storage capacity of more than 8 GWh_{el} has been installed in Spain with this technology. The largest single installation in the USA has a storage capacity of 1.6 GWh_{el}.

As an alternative to the well-established two-tank system, a single-tank molten-salt storage system was developed at Fraunhofer ISE. It offers cost and space savings compared to the current state of the art. In particular, saving space is interesting when storing waste heat from industrial processes. Whereas single hot-water tanks for residential and district-heating applications are very widespread and correspondingly well studied, investigations in the molten-salt field have been restricted mainly to theoretical work or numerical simulation.

The prototype at Fraunhofer now allows the stratification behavior and the effect of different factors to be investigated. These include the difference in density between the hot and the cold media. A large density difference promotes the separation into hot and cold fluid layers. The relative density difference for molten-salt systems is significantly higher than for hot-water systems. This can lead to good storage performance. Another factor concerns heat losses caused by convection currents, which can affect the quality of stratification. The results obtained to date are extremely promising, as very good separation between the hot and cold media was achieved. The vertical temperature distribution is determined with sheath thermocouples; a temperature gradient of more than 120 K over 8 cm was measured. The combination of experimental and analytical results allows us to develop the system further and to prepare systems on a demonstration scale. The goal of subsequent projects will be to replace much of the molten-salt volume with cost-effective filler materials and thus achieve cost savings of more than 30 %.



Vertical temperature distribution in the storage tank during a charging process.

1 *Molten-salt system with temperature-monitoring cables during the construction process.*

2 *Completed molten-salt system.*

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BUILDING ENERGY TECHNOLOGY

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Total staff	**170**
Journal articles and contributions to books	**41**
Lectures and conference papers	**52**
Granted patents	**4**

www.ise.fraunhofer.de/building-energy-technology

More than 40 % of the end energy demand in Germany is caused by the building sector. Similar values apply elsewhere in Europe and in most industrialized countries. Thus, the building sector has a central role to play in reaching climate protection goals. Our aim is to continually reduce the usage of fossil fuels for operating buildings and to avoid it completely in the long term.

Two fundamental approaches are decisive to achieve this aim: On the one hand, the energy demand must be reduced and on the other, the remaining demand must be met by renewable energy sources to the greatest extent possible. Examples of our research and development work include new glazing, which features very low heat losses due to evacuation of the space between the panes, as well as new thermal insulation systems, in which building technical services such as ventilation or heat distribution are integrated into the insulation layer. The latter are particularly important for energy retrofit, as they minimize disturbance to the residents' living space. Other concepts also use the building envelope for active energy conversion, e.g. building-integrated photovoltaics (BIPV). For this application, we have developed powerful tools which can be used for the constructional and electrical engineering planning of BIPV systems, also for geometrically complex building envelopes.

In future, heat pumps will play an increasingly important role in supplying heat to buildings. Our work on heat pumps addresses the entire value chain, from component development for the refrigerant circuit, through equipment and system development, to quality assurance in practical operation. This applies to both electric heat pumps with mechanical compressors and gas heat pumps. For the latter, we are working on new adsorption processes, which achieve both efficient conversion of the drive energy, usually supplied by fuels, and a high power density.

Holistic energy concepts and their planning with digital methods are becoming increasingly important, particularly when applications based on renewable energy sources are to be optimized micro-economically. For example, high fractions of self-consumption for electricity can be achieved by the interaction of photovoltaics, electric and thermal storage units, and heat pumps. However, this type of system requires a powerful energy management system in order to operate stably and reliably – if necessary, by including demand and generation predictions. Operation management concepts and failure analysis procedures, and their implementation in hardware and software, thus represent further important topics which Fraunhofer ISE addresses in its work on building energy technology.

Round copper pipe to which a sheath structure of woven and knitted copper wire has been soldered. The manufacturing technology for metal textile structures allows the enlarged surface area to be tailored to the specifications, e.g. oriented structures or zones of differing density can be created. The illustrated structure improves the sub-atmospheric evaporation of water compared to the current state of the art.

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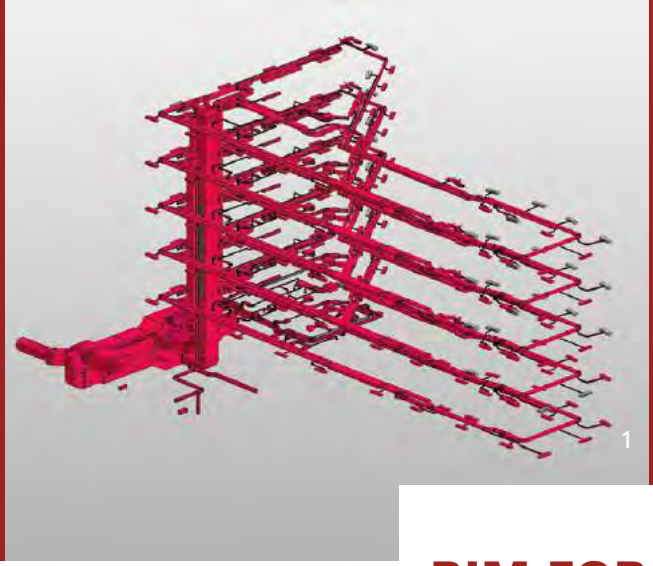
SELECTED PROJECTS IN 2016

- Gas adsorption heat pump with a crystalline zeolite heat exchanger
- Systematic approach for retrofitting buildings
- Sorption cooling system directly integrated into thermal flat-plate collectors
- Mosaic modules as photovoltaic design elements for solar façades
- BIPV on a laboratory building
- Grid-supportive operation strategies for efficient heating and cooling of buildings in the trade, commerce and services sector
- Building control tools tackling the energy performance gap
- Supercooling in micro-encapsulated organic PCM
- Electrically tested BIPV slates for the façade or roof
- BIPV system design for Art Nouveau building
- Comprehensive integration of energetically active façade components into building processes
- Daylight use in buildings – energetic and ergonomic optimization of new lighting systems
- Mapping EU heat supply

Further information on these and other projects:
www.ise.fraunhofer.de/en/research-projects/3-00

New materials / processes
Prototype / pilot series
Software / application
Measurement-based analysis / quality control
Consultancy / planning / studies



BIM FOR INTEGRATED BUILDING AND SYSTEM PLANNING

In the age of smartphones and cloud computing, it is no longer appropriate to print out CAD plans and make handwritten changes at the building site, which may never be entered into the electronic documents. Furthermore, plans which are not kept up to date and the lack of data exchange between the individual trades lead to unnecessary delays and errors during the construction process and the commissioning of a building. A solution should be provided by the methodology of Building Information Modelling (BIM): The real and digital worlds are connected via knowledge-based intelligent systems such that all actors always have access to the current status of relevant information concerning a building or a construction process step.

BIM implies a cultural transformation as architects, planning specialists, building owners, building managers, building companies and people involved in the construction process draw on a central data bank, which is based on a joint, standardized data exchange format. A distinction is made between "open BIM", which applies the internationally recognised IFC standard (Industry Foundation Classes), and "closed BIM", which uses proprietary and manufacturer-specific solutions.

The BIM approach is already widely applied in structural work, e.g. to avoid scheduling conflicts. Geometrical (3D) and technical information about building services can also be integrated into a digital building model and linked to scheduling and cost planning – this is then called "5D". However, up to now an integrated representation of innovative and energy-efficient building envelope components has been missing, as has a description of the functional interrelationships of building services in BIM. In order to plan modern, highly efficient buildings and to guarantee that high demands on comfort and energy efficiency will be met, it is thus necessary to extend BIM.

Fraunhofer ISE is participating actively within various projects to introduce and develop BIM further. For example, the objective of the "SolConPro" project, which is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), is to use BIM to integrate active-solar façades (building-integrated PV and building-integrated solar thermal technology) holistically into the planning process. In doing so, particular attention needs to be paid to the interface between the building-façade and technical-service trades. Another project supported by BMWi, "EnEff-BIM", aims to make complete data exchange between CAD programs and the "Modelica" modelling language feasible. The interface developed for this purpose offers a basis for life-cycle cost analyzes, energy-related evaluation and sustainability certification of buildings. The development of BIM-supported facility management is the main objective of the "Rng-Opt" project.

1, 2 *Digital models of the 3D geometry of buildings and building service technology form an important component of Building Information Modelling (BIM). Beyond geometrical data, the models are enriched with numerous other data sets; these are then used by intelligent systems during planning, construction and operation of the building. This can particularly promote the integration of complex building components, e.g. building-integrated photovoltaics or solar-thermal technology.*

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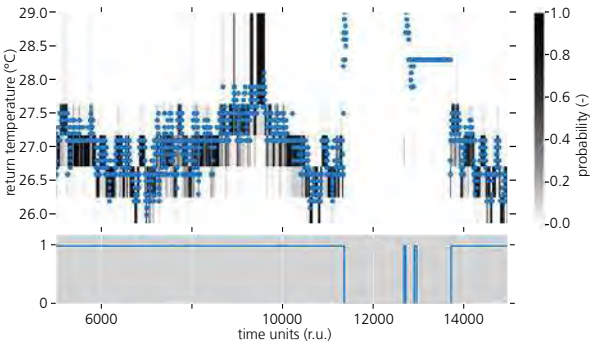
ALGORITHMS TO MONITOR BUILDING OPERATION

Increased demands on buildings with regard to energy efficiency, comfort and safety have resulted in Building Automation Systems developing into communication systems that connect systems from many different building trades and integrate numerous actuators, sensors and functions. With the ongoing expansion of the "Internet of Things", the complexity of building automation systems is increasing further, and the amounts of data generated within such systems are growing continually. However, during the operating phase of a building, high-priority aspects such as ensuring thermal comfort or high energy efficiency are neglected because building operators are not equipped with suitable instruments to analyze the large quantities of data continuously or identify anomalies systematically and in time. According to current estimates, energy savings between 5 % and 30 % could be achieved in many cases by systematic monitoring and optimization of building operation.

Within various projects, Fraunhofer ISE is developing novel algorithms for automatic error detection and diagnosis, which are grounded in data mining and model-based methods. In our work, we are concentrating particularly on supervised learning procedures, which automatically learn the system operation themselves and require little preliminary knowledge about the system and the implemented controls. Promising methods within supervised learning for the building sector include decision trees, clustering and qualitative models.

In the "OBSERVE" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), the application of qualitative models for error detection and diagnosis in building technical plants is being investigated. A function library was developed with the goal of integrating the method into real building automation systems. Within the "HIT2GAP" project, which is part of the European Horizon 2020 Research Programme, Fraunhofer ISE is developing modules for automatic error detection and diagnosis, which are integrated into a novel building management system resembling a smartphone. The BMWi-supported "RngOpt" project and the European "TOPAS" project both address the linking of error-detection methods with Building Information Modelling (BIM). This will provide building operators with contextual information such as technical data or the position of a defect component, so that maintenance work can be optimized.



Qualitative trajectory indicating the state of the return temperature of a thermally activated concrete-core heating system. If the signal in the lower graph becomes zero, this indicates an error.

1 *Building of the regional police department in Mettmann, Germany. The temperatures in the offices are regulated by thermally activated building components such as activated concrete-core components and edge strip elements. The measurement data from the activated concrete core are monitored by qualitative models.*

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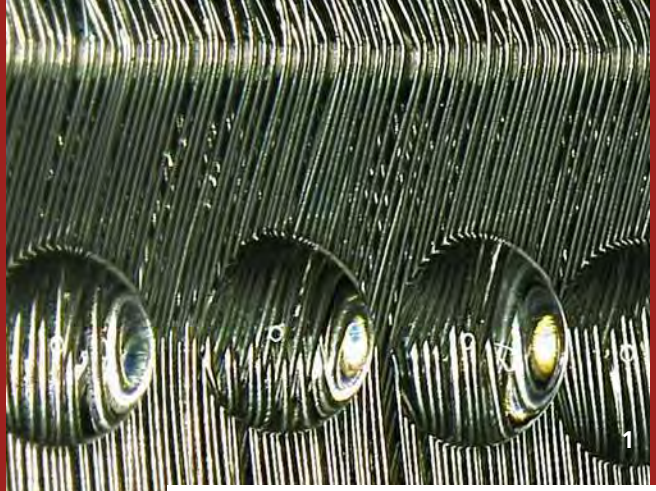

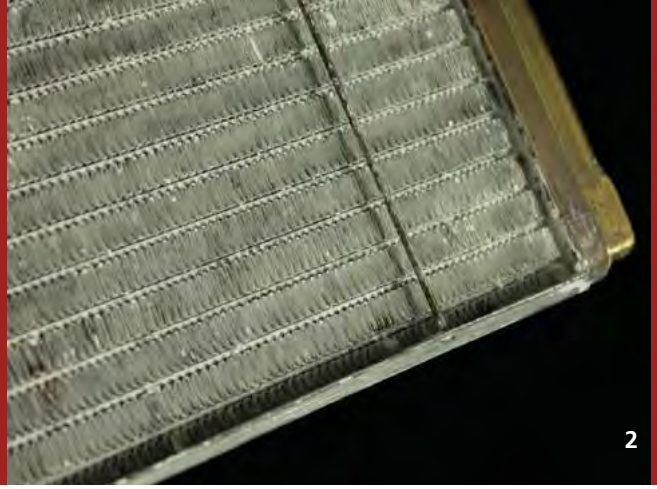

HIGHLY EFFICIENT COMPOSITE ADSORPTION SYSTEMS FOR ENERGY TECHNOLOGY

Thermally driven adsorption heat pumps and cooling systems provide heating and cooling for buildings with high energy conversion efficiency. There are also attractive application possibilities for this technology in the mobility sector and for moisture management in domestic appliances.

The central research and development goal for this topic at Fraunhofer ISE is to provide adsorption modules which simultaneously offer high power density and high efficiency. We achieve this by the interaction between suitable sorption materials, contacting with an optimal heat exchanger (binder-based coating or direct crystalline growth), and the matching of adsorber and secondary components (evaporator / condenser, housing).

Fraunhofer ISE has been working for many years on the development of new sorption materials and improved components for sorption heat pumps and cooling systems. It accompanies manufacturers in all development phases, from selection and evaluation of materials and components, through measurement of equipment according to standards (e.g. VDI 4650-2 or EN 12309) to system evaluation in the field.

During the past year, we achieved several successes in the development of new materials and coatings. We synthesized new metal-organic framework (MOF) materials and successfully upscaled them to application scale. Also, we developed stable, binder-based coatings and adapted them for different adsorbents. They were then applied to different 2D and 3D structures on the heat-exchanger scale. Furthermore, we successfully transferred direct crystalline growth of MOFs onto different geometrical forms and structures.

In the area of composite adsorbents and specific development of heat exchangers, Fraunhofer ISE also reached several important milestones. Among other aspects, we have further developed the methodology for targeted identification of promising structure / material combinations as a function of material properties, coating and system demands. In addition, we identified new potential for saving material and increasing the COP (coefficient of performance) for oriented 3D structures (fibers, wires, meshes).

In the past year, Fraunhofer ISE also developed novel evaporators based on meshes / wires with a high evaporation rate, produced them on a laboratory scale and measured them. We succeeded in tripling the volume-specific rate compared to conventional evaporators.

1 *Wire-based heat exchanger for use as either an evaporator or a condenser.*

2 *Heat exchanger based on fins coated with sorbent for closed sorption systems.*

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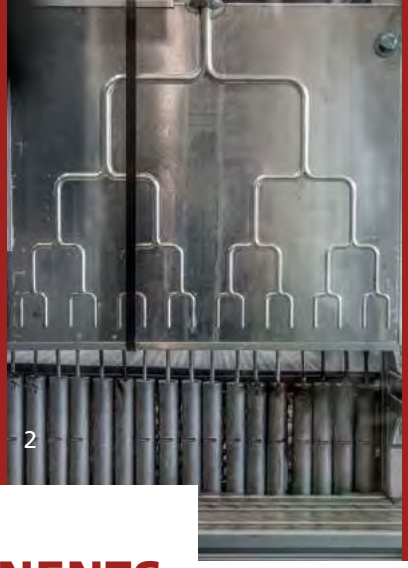

HEAT PUMPS – COMPONENTS, UNITS AND MONITORING

Heat pumps represent a key technology for heating buildings in the future. In combination with an increasing proportion of electricity generated from renewable sources, heat pumps can contribute significantly to a climate-neutral energy supply in the building sector. Fraunhofer ISE supports the development and dissemination of heat pumps (HP) at many different levels.

In the EU-funded "GreenHP" project, new components for air-to-water heat pumps in the high power range were developed, tested and taken into operation within a heat pump system. To develop efficient evaporators, Fraunhofer ISE compared refrigerant distributors and tested their suitability for application under different load conditions. The distribution quality is an important parameter to evaluate the quality of an evaporator. It provides an important indication of how well an evaporator can access the usable energy potential of a heat source. The advantages of the concept of a bionic distributor, which we are investigating, lie in its small internal volume and correspondingly small amount of refrigerant, on the one hand. On the other hand, it is easy to integrate its production into the manufacturing process for soldered aluminium heat exchangers.

For more than ten years, Fraunhofer ISE has been carrying out extensive monitoring projects with heat pumps. We determine the efficiency of heat pump systems and identify optimal solutions for residential buildings. The most recent project, "WPsmart im Bestand" (smart heat pumps in the existing building stock), focuses on the topics of "smart grid" and "hybrid HP". In 2016, about 70 HP systems were equipped with measurement technology; the first results are expected in 2017. Parallel to the empirical investigations, simulations are used to optimize the grid-supportive operation of heat pumps and the pooling of systems to provide energy for controls.

In addition, we carry out projects with various manufacturers to develop equipment especially for the renovation of apartment buildings, an important segment in Germany. These concentrate on the provision of high supply temperatures and large shares of domestic hot water. In the coming years, these should be tested in demonstration buildings within a joint project together with KIT in Karlsruhe and several residential building companies / cooperatives.

In our new test and development center for heat pumps and chillers, we are working together with industrial partners on the development of a number of innovative system concepts for heating and cooling. The innovations include thermally and electrically driven heat pump systems and advanced ventilation concepts. The currently valid standards to measure and evaluate the performance of gas-fuelled heat pumps were investigated in a round-robin comparison within an international cooperation. The measurements provided valuable information to improve the evaluation procedures, which are also relevant for the Energy Label. The laboratory of the center has begun the accreditation process according to ISO 17025 for a series of standards which are relevant for heat pumps. The certified accreditation is planned for 2017.

1 *Demonstration unit for a propane-fueled air-to-water heat pump in the high power range within the "GreenHP" project.*

2 *Detail of the mounted benchtop evaporator with its patented refrigerant distributor.*

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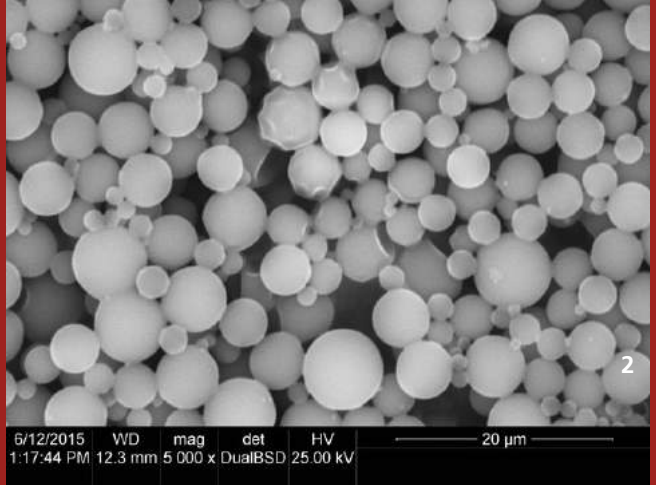

PCM DISPERSIONS STABLE FOR MORE THAN 20,000 CYCLES

When equipment or processes require cooling, there is often a need to remove large amounts of heat while maintaining only a small temperature difference within the heat transfer medium. One solution is provided by dispersions of a phase change material (PCM) in water. We develop dispersions with paraffin as the PCM and water as the liquid, which feature significantly higher thermal storage density in a narrow temperature range around the melting point of the PCM than pure water. For temperature differences of less than 10 K, the dispersions that we have developed achieve storage densities that are up to three times higher than that of pure water. The resulting PCM heat-transfer slurry remains a fluid, independent of the physical state of the PCM, and can thus be pumped. Tensides are added to stabilize the PCM dispersions. Because of the phase change, the tensides must stabilize both the liquid and the solid phases of the PCM. In addition, the PCM dispersions experience large shear forces in application, particularly in centrifugal pumps and heat exchangers.

In order to test whether PCM dispersions remain stable under shearing stress, we tested them in hydraulic test rigs under conditions similar to those found in application. These test rigs are equipped with standard components such as centrifugal pumps, plate heat exchangers, membrane expansion vessels and valves. For the thermal cycling, the PCM dispersions are circulated between two plate heat exchangers, whereby the PCM crystallizes and melts again once per cycle.

With the help of this test rig, we successfully subjected one of the PCM dispersions we developed, with 35 weight-percent paraffin, to more than 20,000 thermal cycles and simultaneously exposed it to the high shear forces that occur in the components. This demonstrates our success in developing PCM heat transfer fluids that are very stable.

It became evident that the dispersed PCM experienced strong super-cooling due to the separation of the existing heterogeneous crystallization nuclei that occurs during dispersion. To counteract this effect, we screened many materials in the search for one which shows good nucleation behavior and is simultaneously stable in the PCM particles also during phase changes. We succeeded in finding materials which significantly and reliably reduce the super-cooling, even for very large numbers of cycles.

As a result, PCM dispersions are now available for experimental investigations in different applications, which range from utilization for building cooling, e.g. in cooling ceilings and storage units for cooling power, to battery cooling for stationary and mobile applications.

1 *Emulsion in a storage tank.*
2 *Microscopic image of a PCM dispersion.*

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HYDROGEN TECHNOLOGIES

Stacked unit for CATVAP (catalytic evaporation process) to reduce emissions and increase the efficiency of combustion motors.

Interview with
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Total staff	**72**
Journal articles and contributions to books	**4**
Lectures and conference papers	**18**
Granted patents	**3**

www.ise.fraunhofer.de/hydrogen-technologies

How should hydrogen technology be applied to achieve a successful energy transformation?

The strength of hydrogen lies in the diverse ways it can be used as a fuel that can be stored and transported. Hydrogen can be produced by electrolysis of water using electricity generated from renewable sources. It can then be used as a secondary form of energy as required in diverse applications within and between different sectors. This can be in sustainable mobility based on fuel-cell vehicles, in the chemical industry as a raw material or within the energy economy.

What should be done to achieve a breakthrough in using hydrogen to store energy for supplying electricity?

The most important aspect here is to create appropriate legal boundary conditions. Within the energy economy today, electrolysers are treated as final consumers, regardless of their intended application. This results in very high levellized costs for hydrogen production, which are not (yet) competitive with conventionally produced hydrogen.

Which challenges currently face electrolysis technology and which research approaches are you applying to address them?

Primarily PEM electrolysis still offers great potential for cost reduction. Our cost models demonstrate impressively how costs can decrease dramatically when the cell area is scaled up. An increase in the current density also enables considerable cost reduction. However, our work is concentrating mainly on understanding aging mechanisms better at the cell level, so that the lifetime of electrolysers can be lengthened.

Why does Fraunhofer ISE consider itself to be well prepared for further developments in hydrogen technology?

With its developments on efficient electrolytic production of hydrogen, the utilization of hydrogen in fuel-cell systems and the conversion of hydrogen into liquid fuels and chemicals by use of CO_2 (Power-to-liquid, PtL), Fraunhofer ISE is making decisive contributions toward the commercial introduction of this technology.

The German Federal Government has been subsidizing the purchase of electric vehicles for some time. What potential does fuel-cell mobility have and how should it be supported?

Fuel-cell mobility enables ranges and tank-filling times which are comparable to modern combustion engines. At the same time, hydrogen can be produced regeneratively, so that fuel-cell vehicles hold promise for mobility which is free of emissions both locally and globally. Adequate infrastructure is essential for its market introduction and is currently being expanded with public support within the "H_2Mobility" industrial initiative.

What is the current status of research on fuel-cell technology?

Research is supporting the development of future generations of vehicles beyond 2023. The most important challenges are to continue to reduce costs and especially to minimize the amounts of noble metals used. Furthermore, scientific questions concerning long-term durability and sensitivity to contamination need to be answered.

Thermochemical processing procedures belong to your business area. What are the most important tasks?

The goal is to reduce emissions with our technology, particularly in the transport sector. We have two solutions to offer: An evaporation process for liquid fuels that was developed at Fraunhofer ISE allows customized adaptation of the combustion properties to the relevant application (engine, burner, etc.), which can drastically reduce the emission of NO_x and soot, and increase the efficiency. If this is combined with our synthesis of PtL fuels such as oxymethyl ethers (OMEs) from sustainably produced hydrogen and CO_2, CO_2 emissions can also be significantly reduced at the same time.

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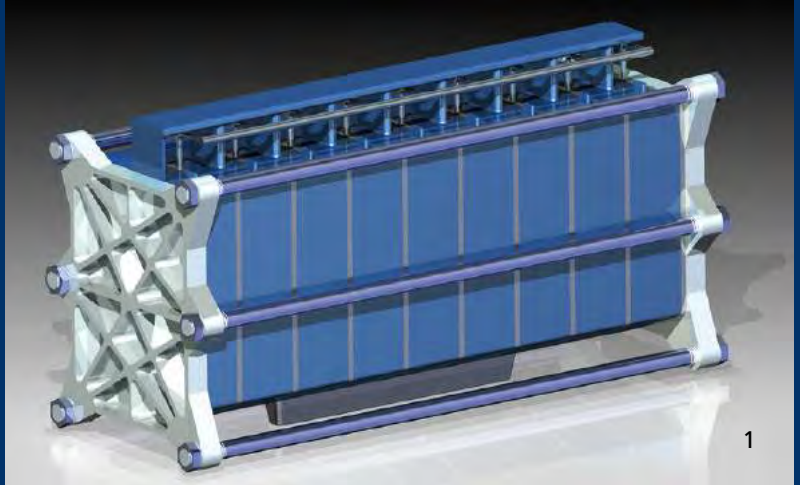
More information on R&D projects in this business area:
www.ise.fraunhofer.de/en/research-projects/4-00



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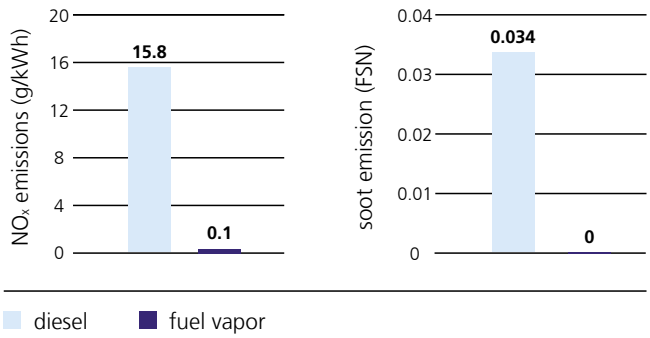
NEW PROCESS REDUCES EMISSIONS FROM COMBUSTION ENGINES

The car industry is facing an enormous task. Law-makers are specifying increasingly stringent limits for nitrogen oxides (NO_x) and soot particles. At the same time, the emission of the greenhouse gas, CO_2, should be reduced drastically. To date, the emission of soot particles and NO_x is being reduced by post-combustion treatment of the exhaust gases in soot particle filters, by selective catalytic reduction (SCR) and/or NO_x storage catalysers, in combination with measures inside engines (cooled exhaust gas recovery and air intake). Exhaust aftertreatment systems are expensive due to the large amount of noble metals they contain, and are heavy, thus increasing fuel consumption.

These are the starting conditions for the CATVAP technology development at Fraunhofer ISE. The catalytic evaporation process (CATVAP) is a method to optimize combustion processes which reduces emission and can be applied for many different fuels. It was trademarked in 2016.

The method is based on a catalytic process with which fuels such as diesel, petrol and biodiesel can be evaporated, free of residues. The CATVAP is scalable and can also be applied for large combustion engines from the heavy-duty sector. Its planar configuration means that high evaporation rates can be achieved for the first time in a very compact unit and can be adapted to the power of each specific application. The fuel vapor is fed into the intake pipe of the engine and mixes there homogeneously with the combustion air. This measure drastically reduces the emission of soot and NO_x in comparison to conventional combustion already in the engine. The fuel vapor has different fuel properties and thus other ignition properties to the initial fuel. This allows the combustion to be controlled and optimized. This has already been demonstrated successfully with a single-cylinder test engine using diesel. By changing the fuel properties, it was still possible to control the 50 % mass fraction burnt point at higher load operation.

The NO_x emissions were reduced far enough that the limiting value for the Euro 6 standard was reached without additional exhaust treatment in the tested area of the engine map. At the same time, the soot emissions were far lower than those from conventional diesel combustion, and the fuel consumption was very low. In addition, we demonstrated that the chemical modification of the fuel in the evaporator reduces the knocking tendency of petrol. This allows the efficiency of petrol engines to be increased and CO_2 emissions to be reduced.



Significant reduction of NO_x and soot emissions achieved by using the catalytic evaporator, compared to conventional diesel combustion.

1 *3D stack design of the catalytic evaporator with a volume of 1 liter and for thermal power inputs up to 150 kW.*

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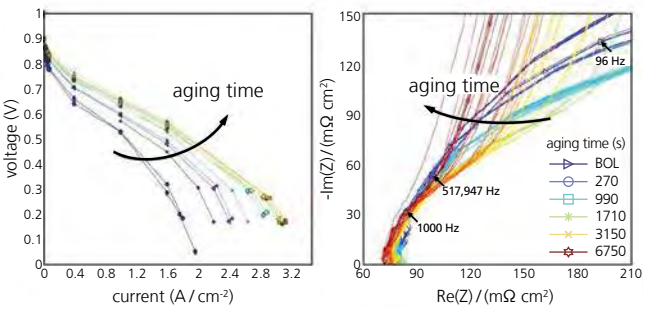
MEMBRANE ELECTRODE ASSEMBLIES FOR PEM FUEL CELLS

For large-scale production series, the catalyst layer equipped with noble metal catalysts is the cost-determining component of a fuel-cell vehicle. The performance of the catalyst layer is determined by its structure, i.e. the interaction between the catalyst material (usually platinum alloys), the catalyst support (electron conduction) and the ionomer (proton conduction). A highly porous structure of the electrode enables diffusion of the reaction gases, oxygen and hydrogen, and removal of the produced water.

At Fraunhofer ISE, a reproducible process for cost-effective production of membrane electrode assemblies was developed. After preparation of the paste, which consists of the catalyst, the catalyst support, the ionomer and a solvent, various printing processes are used for coating. To optimize the dry layer structure, we have developed a novel impedance model to understand the electrochemical processes in the catalyst layers. Long-term stability is investigated using various accelerated aging procedures.

In one study, a maximal cell power was identified for an ionomer content at the beginning-of-life (BoL) of between 30 and 35 weight percent. With the assistance of the impedance model, we recognized that insufficient protonic bonding to the membrane was the main reason for the power reduction at lower ionomer content. Contrary to prediction, however, accelerated aging tests of the layers with a low ionomer content revealed a clear improvement in performance. At an aging voltage of 1.2 V, the power equalled that for higher ionomer content already after a short time. The impedance model indicated that the power increase was caused by increasing protonic conductivity of the catalyst layer and improved bonding to the membrane. These positive effects clearly overcompensate for the negative effects of catalyst support degradation at the beginning of the aging. The insight gained allows the development of catalyst layers with a significantly lower ionomer content and thus improved oxygen transport properties. In addition, the results demonstrate that it is important to take changing properties into account when optimizing the catalyst layer.



Improvement of the current-voltage characteristic curve (left) and change in the impedance spectra (right) for a catalyst layer with an ionomer content of 15 weight-percent during 6750 s aging at 1.2 V.

1 *The fuel cell laboratory at Fraunhofer ISE.*

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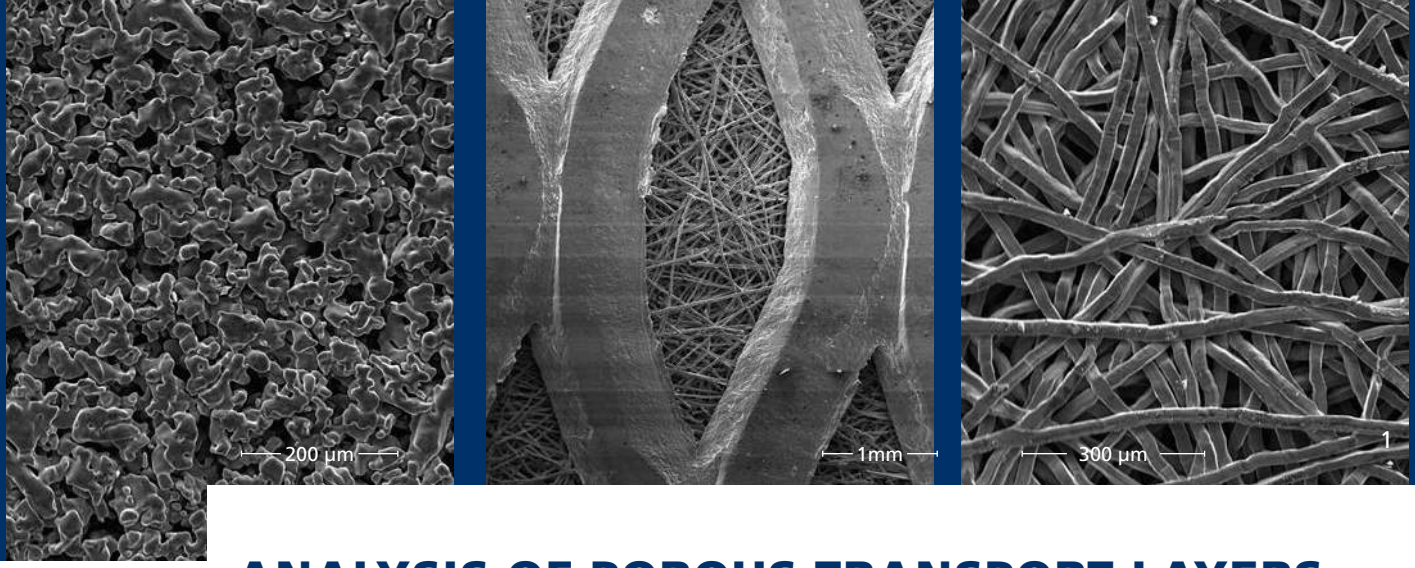

ANALYSIS OF POROUS TRANSPORT LAYERS IN PEM ELECTROLYSIS CELLS

The electrochemical splitting of water using PEM-electrolysers is a clean and efficient process to produce hydrogen. When the input electricity is generated from renewable sources, green hydrogen can be produced as a universal fuel that can be stored and later used in different applications of the energy sector, the transport sector or the chemical industry.

Primarily PEM electrolysis, applying proton exchange membranes, is well suited for connection to renewable energy, as this process enables very high efficiency values for high current densities and simultaneously demonstrates fast dynamic transient behavior.

The core component of every PEM electrolysis system is the electrochemical unit, the electrolysis stack. It splits water into its components, oxygen and hydrogen. One of the essential components of the stack is the so-called porous transport layer (PTL), which is responsible for fluid-transport, electrical and mechanical tasks. On the one hand, the reagent water must be transported through this layer to the electrocatalytically active layer (the electrode); on the other hand, the gaseous reaction products must simultaneously be removed from the electrode. Furthermore, the PTL closes the electric circuit between the external electrical connection and the electrode. The PTL must thus be as electrically conductive as possible. Mechanical compressibility is a further important material parameter, as it determines the contact resistance between the PTL and the electrode. For the anode side of the electrolysis cell, strongly oxidizing conditions also exist due to the low pH value, the high electric potentials and high temperatures, combined with oxygen production.

In order to meet these specifications, Fraunhofer ISE is investigating porous structures based on titanium from different production processes and with different coatings. Various in situ and ex situ methods are applied to characterize the PTL, such as determination of the current-voltage characteristics and fluidic permeability for gas-water mixtures. Based on these data, novel structures and materials can be developed and tested for their suitability as PTL in PEM electrolysis cells.

1 *SEM images of different PTL structures: left: sintered Ti powder. center and right: Ti hybrid consisting of sintered fibers and mesh.*

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ENERGY SYSTEM TECHNOLOGY

Prof. Bruno Burger
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Total staff	**159**
Journal articles and contributions to books	**15**
Lectures and conference papers	**20**
Granted patents	**2**

www.ise.fraunhofer.de/energy-system-technology

Energy systems technology optimizes the interaction between generators and consumers, their control and regulation as well as the management of energy distribution and storage. It is one of the most important fields of work for the energy transformation and is thus one focus in our portfolio.

Our spectrum ranges from energy systems analysis, through the optimization of energy systems, to the development of battery systems, power electronic components or information and communications technology solutions. An invaluable advantage here is that in designing and optimizing at the system level, we can also draw on well-founded technological experience with energy supply components such as PV modules, storage elements or CHP plants within the Institute.

Our work concentrates on the conception and optimized operation management of sustainable energy supply systems for buildings, urban neighborhoods, industrial plants and energy supply systems up to the national level. This also includes supply structures such as the electricity grid and heating networks as well as the mobility sector, for which we are preparing new solutions to integrate electric vehicles into electricity grids. An essential aspect of our work is to treat different energy forms such as electricity, heat and gas holistically when we are conceiving modern energy systems that are defined by fluctuating generation. This allows maximal flexibility and the most economic usage of energy. To do this, we are developing innovative solutions for control and communicative networking at both the component and the system level.

Battery systems have long been a standard component of autonomous energy systems. However, their significance in grid-connected systems is also growing rapidly. We offer a broad spectrum of R&D services for lead-acid, lithium-ion or redox-flow systems. Part of our new center for storage technology is an extremely modern laboratory, in which, along with the development of redox-flow batteries, primarily battery systems can be designed, analyzed, tested and optimized with regard to operation management.

We are also developing power-electronic components and systems for many application areas. The major topics are inverters, transformers, converters and controls for use in energy supply and transmission, both for stationary and mobile applications. Particular attention is paid to optimal integration into the entire system and achievement of the greatest energy efficiency.

A pilot project with the largest agrophotovoltaic (APV) system in Germany was officially commissioned on 18.09.2016. On this occasion, the award for "Landmark in the Land of Ideas" competition was also presented. Fraunhofer ISE cooperated with partners to install the APV pilot system on the land of the Demeter farming community of Heggelbach. The installed power of the APV system of 194 kWp can meet the electricity demand of around 62 households.

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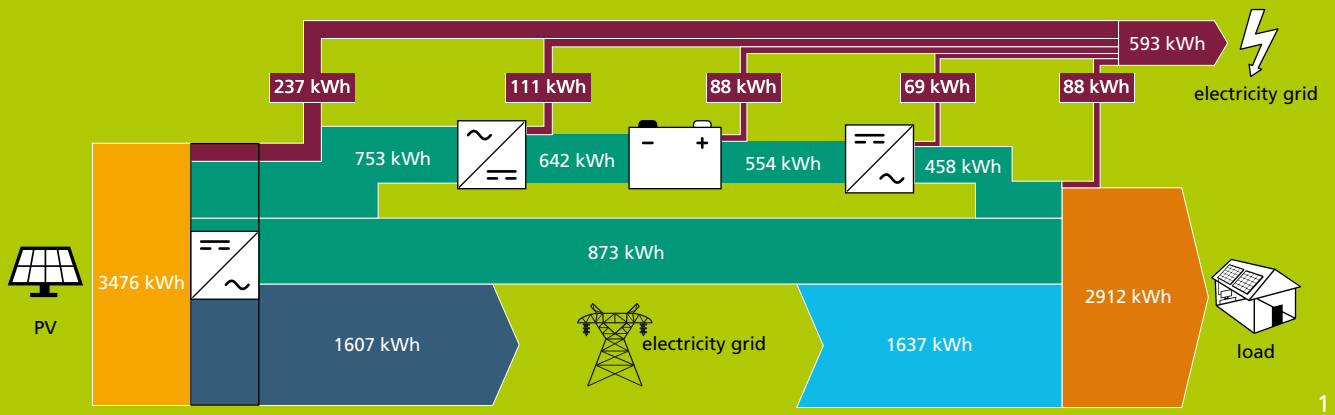
SELECTED PROJECTS IN 2016

- Efficient, highly compact high-frequency power electronics with GaN transistors
- Bidirectional, inductive charging systems
- Energy and economic efficiency for smart communities through integrated multi-storage technologies
- Optimized self-consumption system for commercial and industrial use
- Innovative solutions for new, highly integrated PV inverters in the power range from 30 to 70 kW
- iURBAN: intelligent iURBAN energy tool
- Development of a cost-efficient smart grid communication system based on ripple control
- Test stand for development and testing of fuel saver devices and strategies in PV-diesel grids
- Second life of lithium-ion traction batteries in mobile and stationary applications
- Complementary usage of different energy supply concepts as a motor for social acceptance and individual participation

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/5-00

New materials / processes
Prototype / pilot series
Software / application
Measurement-based analysis / quality control
Consultancy / planning / studies

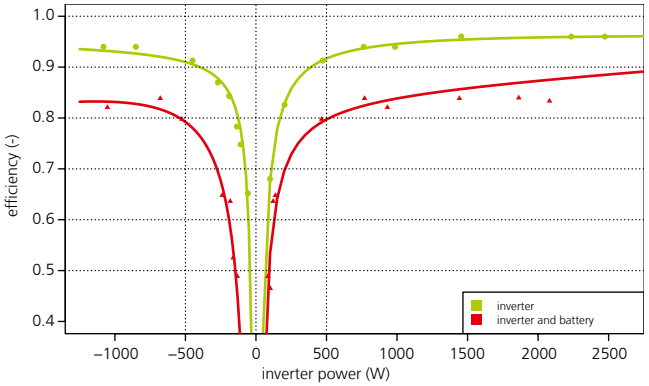


1

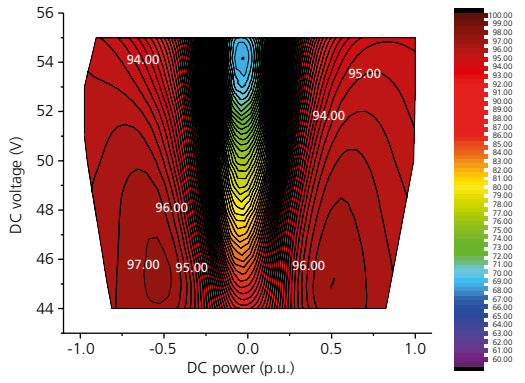
EFFICIENCY OF BATTERY-INVERTER SYSTEMS

The further the price falls for highly efficient storage systems, the more widespread they become in stationary applications. However, further innovations are needed with respect to their economic viability, long-term stability and efficiency. Their efficiency is determined particularly by the efficiency value of the power electronics in the inverter. The partial-load efficiency is at the focus of attention, as it makes supplying power from the battery inefficient for a small load. We are thus working on the control accuracy and dynamics of the power converters and the circuit topology. DC high-voltage systems, which usually demand the integration of the PV system and a high-voltage battery, are efficient. However, AC-connected variants of the battery are also important. Most commercially available systems have a low voltage level of 48 V for the battery, which necessitates an additional DC/DC converter, which in turn affects the system efficiency negatively. Another challenge is to reduce the parasitic consumption for measurement and control technology, so that the high standby losses of many products decrease. We are developing and optimizing operation management systems for the standby and wake-up processes, which will allow the battery system to be switched off when too little power is being transferred. In addition, we are working on concepts to integrate the energy management system and control technology into power converters for efficient operation.

In our accredited TestLab Power Electronics, we accurately characterize power electronic components with respect to their efficiency and control properties. Furthermore, we have a laboratory for dynamic measurement of batteries and battery systems during operation. In our ServiceLab SmartEnergy, we can measure complete systems under typical application conditions. We use system simulation models to represent system properties dynamically and obtain information on effective utility factors and efficiency values over an entire year.



Efficiency of a 48 V DC battery inverter for discharging (positive power) and charging (negative power) relative to the DC side.



Efficiency value of a battery inverter as a function of the DC power and DC voltage.

1 *Sankey diagram for a commercially available PV-battery system, which suffers large losses when the battery is charged or discharged.*

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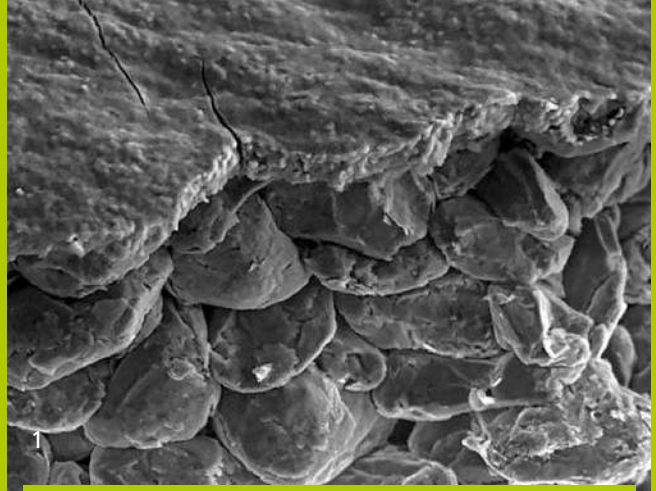

LIFETIME OF BATTERY SYSTEMS – PREDICTION AND OPTIMIZATION

Fraunhofer ISE is addressing many aspects concerning the lifetime of batteries. We analyze the aging of lithium-ion batteries, taking their application-specific utilization profile into account. Our aim is to identify operating conditions and operation management strategies which affect the lifetime positively. In post mortem investigations, we open aged battery cells and investigate them with the objective of determining the physico-chemical processes leading to the degradation of the cells. From this, we derive methods to delay or largely prevent these processes. For aged lithium-ion cells used beforehand in electric vehicles, we investigate second-life alternatives for usage, e.g. in stationary applications. To this purpose, we set up models for usage-dependent lifetime prediction and residual value. These can be used to predict whether a second-life application is economically reasonable. In addition, we are working on improvements in thermal management. On the basis of system simulation models, we investigate strategies for demand-relevant cooling and heating. For this we develop control algorithms, which are subsequently implemented in a battery management system. Furthermore, we investigate the use of battery storage units as an option for flexibility in the electricity grid. The goal is to develop a model-based procedure for on-line diagnosis and application-specific, in situ aging prediction, and to implement this in a management system that is available for large storage systems.

1 *SEM image of a graphite anode of a lithium-ion battery cell in an aged, non-linear state.*

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INNOVATIVE CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES

Around 18 % of the CO_2 emissions in Germany originate from the transport sector. Electric vehicles are therefore central elements of the energy transformation. We have been working for many years on intelligent integration of the charging systems into the electricity grid. This includes reacting smoothly to fluctuating generation and also preventing the distribution grids from overloading during peak hours. Apart from the technical aspects, the decisive questions are how much which service is worth and whether it should be provided within regulated sectors or on the free market.

One current topic is the investigation of the specific added value of a bi-directional, inductive charging infrastructure. In addition to the greater convenience, the main advantage of the wireless technology is that part of the power electronics is permanently connected to the electricity grid. Thus, certain grid services can be used, even when no vehicle happens to be connected. By providing reactive power at the company location to maintain the voltage or to compensate higher harmonics, bidirectional charging infrastructure can become an economically interesting alternative to conventional technology. In a smart home, prediction-based charge control allows optimal utilization of the PV electricity generated on site. As demonstrated in various research projects, this not only offers the user ecological and economic advantages, but also reduces peaks in generation and loads at the building connection to the grid.

2 *Coil for wireless energy transfer between a charging station and an electric vehicle.*

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3

COMPACT AND EFFICIENT POWER ELECTRONICS WITH GaN AND SiC SEMICONDUCTOR COMPONENTS

The efficiency of mobile systems is determined not only by the efficiency of power electronic systems, but can also be increased by weight reduction. By saving weight and thus fuel, an aeroplane for example, considered as a complete system, can gain efficiency. Also, the amount of exhaust released, which is particularly damaging at high altitudes, can be reduced. In this way, both direct economic savings can be achieved and ecological damage can be reduced. Extremely modern power semiconductor components based on gallium nitride (GaN) and silicon carbide (SiC) make it feasible to operate power-electronic circuits at significantly higher switching frequencies than conventional transistors based on silicon (Si). This allows the power density with respect to volume and weight to be increased and the materials costs to be reduced at the systems level. These advantages are particularly relevant for mobile systems. Accordingly, within the "GaN-resonant" project, we developed a DC-voltage converter with a power density of more than 3.8 kW/dm^3 for aeronautics. In the "GaNPV" project, a 2 kW PV inverter was implemented with a switching frequency of 250 kHz. This allowed the power density compared to conventional products to be increased by a factor of about five, while the efficiency value remained unaffected. These good results can also be transferred to other application areas such as classic power supplies.

3 *Technological demonstrator of a 1.5 kW resonance converter with a switching frequency of 2.5 MHz.*

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4

OPERATING ELECTRIC STORAGE UNITS ECONOMICALLY

Electric storage units are needed in the long term to integrate renewable energy sources into the future energy system. However, at present there are hardly any incentives for investors to become active in this area. The German pumped storage power plants currently have difficulty in refinancing themselves. Although the market for battery storage units has grown appreciably in recent years, it is still dependent on subvention, despite markedly reduced costs. It is particularly important to develop the market as early as possible by introducing economic operator models.

Fraunhofer ISE has developed models and methods with which the economic viability of energy storage can be estimated under different conditions. The "ENTIGRIS Unit" model allows the economic viability of technology such as electricity storage units to be investigated in different application areas. Falling storage prices, different developments in the electricity market, increasing electricity costs for households and industry, new tariff structures and changed regulatory boundary conditions affect the economic viability of electricity storage and are reproduced in the model. Based on the results, specific recommendations can be derived for action by operators of energy storage units, investors and politics.

4 *Battery bank and PV system in a free-standing house – a popular business model in Germany.*

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1

CALLAB PV CELLS

PHOTOVOLTAICS ACCREDITED LABORATORY

CalLab PV Cells

CalLab PV Cells at Fraunhofer ISE offers the calibration and measurement of solar cells from a wide range of PV technology and works with companies and institutes at national and international levels to develop accurate measurement methods for new types of technology. It is one of the internationally leading photovoltaic calibration laboratories and 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.

CalLab PV Cells is accredited according to ISO/IEC 17025 as a calibration laboratory for solar cell calibration with the Deutsche Akkreditierungsstelle DAkkS. With the support of the German Federal Ministry for Economic Affairs and Energy (BMWi) and in cooperation with PV manufacturers, we work continuously on reducing uncertainties and developing new measurement procedures. The change in solar cell parameters at higher temperatures plays an important role for their yield in practical applications. A new procedure with which the temperature-dependent behavior can be determined with a previously unattainable accuracy has proven to be very attractive for manufacturers of solar cells. We apply this and other special measurement in a project to optimize the maximum annual yield of high-efficiency solar cells using highly accurate analysis based on the dependence of cell parameters on temperature and irradiance level.

In order to guarantee the comparability of measurements for solar cells from different types of PV technology, we develop measurement procedures for novel solar cells. New metallization structures on wafer-based solar cells and new material combinations for the absorber, as in perovskite solar cells, are specific aspects addressed by our new developments. Various multiple-source simulators allow us to make measurements under almost any standard conditions, such as AM0 (ISO 15387) for space applications and AM1.5d (ASTM G173-03) for concentrator applications. Using our spectrally adaptable flash lamp simulator, multi-junction cells with up to four pn junctions can be measured under concentrated radiation with appropriate simulator spectra. In addition, we are supporting the development of standards on concentrating and non-concentrating photovoltaics in the working groups WG 2 and WG 7 of technical committee TC 82 of the IEC.

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Multi-Junction and Concentrator Cells
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- Continuous and flash lamp solar simulators meeting stringent specifications on spectral distribution and lateral homogeneity
- Measurement units for accurate calibration of multi-junction solar cells
- Contacting devices for almost all types of solar cells
- Shade-free measurement of cells with interrupted bus bars
- Measurement of the spectral response for all types and dimensions of solar cells
- Characterization of the conformity of solar simulator radiation with IEC standards

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

CALLAB PV MODULES

PHOTOVOLTAICS
ACCREDITED LABORATORY

CalLab
PV Modules

In our accredited calibration laboratory, CalLab PV Modules, we combine comprehensive scientific know-how with modern measurement technology. Our clients include renowned module manufacturers, EPCs (engineering, procurement, construction) and investors with the highest demands on quality. They value our many years of experience and our excellent reputation in the field of module characterization.

Our service offer ranges from the calibration of single cells and modules to customized tasks such as the calibration of bifacial modules. Our measurement uncertainty of only 1.6 % and our quality assurance measures make us international leaders. In CalLab PV Modules, modules are characterized comprehensively according to the Energy Rating Standard, IEC 61853, and module quality is evaluated on the basis of individual testing procedures. CalLab PV Modules supplies and calibrates client-specific reference cells that we developed in house (WPVS Standard and LARC) for different applications. A new type of cell based on negatively doped silicon material (n-type) with greater sensitivity in the IR range was successfully integrated and the configuration of the reference cell was optimized at the same time. As a result, adapted reference cells for new cell technology (e.g. PERC) are now available to our clients for the first time.

For accurate long-term characterization of PV modules in outdoor operation, CalLab PV Modules is offering a newly developed data acquisition system. The measurement system has a modular structure and records high-resolution DC measurement data (IV curves) of individual modules. This allows laboratory measurements to be verified and complements comprehensive characterization of modules with respect to the yield properties for new types of technology like bifacial modules. CalLab PV Modules offers this new service throughout the world. The data analysis by Fraunhofer ISE can be adapted according to the client's requirements, so that all relevant parameters are available with the highest accuracy to our clients. We can measure the power output from concentrator PV modules (CPV) under standard conditions using several outdoor test rigs equipped with trackers or in the laboratory with a solar simulator. The rating procedures used are documented in the IEC Draft Standard 62670-3. Fraunhofer ISE is actively involved in developing this standard, which was recently accepted by the IEC as a New Work Item Proposal (NWIP).

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- Accurate measurements according to IEC 60904-3 with a measurement uncertainty of only 1.6 %
- Determination of the spectral response at the module and cell level from 300 nm to 1200 nm
- Power Rating measurements according to IEC 61853
- Determination of the angular dependence according to IEC 61853-2
- Determination of the low-light performance down to 100 W/m²
- Measurement of temperature coefficients over the range from 15 °C to 75 °C
- Characterization of bifacial PV modules
- Supply and calibration of WPVS and LARC reference cells
- Evaluation of CPV modules under CSOC and CSTC

1 *New test stand developed by Fraunhofer ISE for calibration of bifacial PV modules.*
2 *New WPVS reference cell (n-type) with greater sensitivity in the IR spectral range.*

1

TESTLAB PV MODULES

PHOTOVOLTAICS

ACCREDITED LABORATORY

TestLab PV Modules has offered a broad spectrum of services focussing on quality and reliability testing since 2006. Our laboratory, which is accredited according to ISO 17025, is equipped with state-of-the-art and innovative testing facilities that can be used for applications extending well beyond standard testing procedures.

Testing Specific to Clients' Requirements and Applications

We advise our clients in the definition of cost-effective and efficient testing programs as well as on individual quality criteria, depending on the concrete question. The tests can serve to detect potential weaknesses in a module, compare different module types by benchmarking or assess the suitability of a specific type of module for particular application conditions.

Analysis of Defects and Risk Minimization

We apply innovative and recently developed analytical methods to systematically investigate defects such as so-called snail trails and potential-induced degradation (PID). TestLab PV Modules offers specific tests and test sequences for many typical defects.

Accuracy

Highly accurate power measurements are carried out in our accredited calibration laboratory, CalLab PV Modules, with an internationally leading measurement uncertainty of down to 1.6 %.

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 61215-1/-2:2016, IEC 61730-1/-2:2016).

Quality Control for the "VDE Quality Tested" Certificate

Together with the VDE Prüf- und Zertifizierungsinstitut, we have developed a quality certificate for PV modules which enables ongoing quality control of module production by an independent body at a high level. We also carry out these module tests in our TestLab PV Modules.

TestLab
PV Modules

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www.testlab-pv-modules.de

- Accredited testing laboratory according to ISO 17025 for IEC 61215, IEC 61730
- Failure and materials analysis (e.g. EDX, Raman, Auger spectroscopy)
- Non-destructive analysis (e.g. lock-in thermography, EL, microscopy)
- In situ monitoring
- Climatic test chamber with UV radiation
- Climatic test chamber with integrated solar simulator
- Mechanical load tests at different temperatures and mounting angles
- Sand abrasion tests
- Salt spray test IEC 61701

1 *The hot-spot test (IEC 61215) is carried out in our double climatic chamber with a solar simulator.*

TESTLAB SOLAR THERMAL SYSTEMS

SOLAR THERMAL TECHNOLOGY
ACCREDITED LABORATORY

TestLab
Solar Thermal
Systems

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

Since 2012 we have intensively investigated different aspects concerning the mechanical reliability (at temperatures between -40 °C and 90 °C) of mounting systems, PV modules and solar thermal collectors. The service spectrum here is also designed to address the requirements of the DIBt (German Institute for Building Technology). Together with TestLab PV Modules, we offer measurements for complete certification of PVT collectors (IEC and ISO). We are equipped with a well-established solar air-heating collector test stand. Based on our technical characterization, Solar Keymark certifications have been carried out for many solar air-heating collectors.

Further measurements can be carried out in our systems and storage tank laboratory. This is where the coefficients needed to evaluate tanks according to the Energy Label (ErP) of the EU are determined. Our solar simulator achieves high reproducibility, which makes the test stand very attractive also in a developmental context. With the further development of in situ characterization, new application options within the context of extended collector certification have been created at TestLab Solar Thermal Systems. Our testing is fundamentally based on the updated version of EN ISO 9806:2014. We are actively accompanying the newest revision of the collector testing standard. This standard will be applicable for all types of collector technology included in its scope and for all modifications to the testing methods within the scope of our accreditation. This is unique to our laboratory.

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Storage tanks, systems
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- Measurements for the Energy Label according to ErP
- Mechanical load tests (e.g. DIBt)
- Certification measurements for
  - air-heating collectors
  - PVT hybrid collectors
  - concentrating collectors
  - flat-plate and evacuated tubular collectors, with test duration of less than 1.5 months (on request)
  - thermal storage tanks
  - prefabricated systems
- Field measurements, monitoring and in situ certification
- Highly accurate measurements for optimizations (e.g. solar simulator)

1 *Hot water tank being tested for the EU Energy Label (ErP) at the TestLab Solar Thermal Systems.*

TESTLAB SOLAR FAÇADES

BUILDING ENERGY TECHNOLOGY

ACCREDITED LABORATORY

TestLab
Solar Façades

In TestLab Solar Façades, we characterize transparent and translucent materials, test building components and evaluate the energy-relevant, thermal and optical properties of complete façades. This encompasses both "passive" façade components like glazing and solar-shading devices, which offer classic functions such as thermal insulation, solar control and daylighting, and also "active" façade elements which convert solar energy into electricity or heat.

Accredited Testing of Optical Properties, g Value and U Value

The laboratory is accredited according to DIN EN ISO/IEC 17025:2005 for determining g value, transmittance, reflectance and U value by calculation and measurement. Our speciality is testing objects which often cannot be characterized adequately by conventional testing methods, e.g. building components with angle-dependent properties, light-scattering materials or structured and light-redirecting elements. The services of TestLab Solar Façades are also used for sectors that are not related to building façades (e.g. determination of the Solar Reflectance Index – SRI – for roofing and paving materials).

Complete Energy Evaluation of Passive and Active Façades

We have extensive research experience in solar-control systems, building-integrated photovoltaics (BIPV) and building-integrated solar thermal technology (BIST). We have specialized in the mathematical and physical modelling of optical, thermal and PV electric processes in sunlit façades and analysis of their effects on the energy performance of buildings.

Daylighting and Glare Evaluation

BSDF data sets (bi-directional scattering distribution function) are determined goniometrically and can be used in simulation programs to evaluate daylight use and glare, e.g. for offices with sophisticated window and sun-shading systems. Studies on user preferences and visual comfort are carried out in rotatable daylight measurement rooms.

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Daylighting Test Rooms
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- Modelling and measurement of passive and active façade elements
- g value test stands (angle-dependent; indoor and outdoor)
- 3D goniometer to determine BSDFs
- Large integrating spheres for angle-dependent spectral measurements

1 *Transmittance measurement of structured building components and elements (here: partly transparent façade collector).*

TESTLAB POWER ELECTRONICS

ENERGY SYSTEM TECHNOLOGY

ACCREDITED LABORATORY

TestLab
Power Electronics

In TestLab Power Electronics, which is accredited according to DIN EN ISO/IEC 17025, power electronic equipment with a power rating into the megawatt range can be characterized. DC sources with a total power output of 1.4 MW are available for this purpose. They can be flexibly parametrized and simulate e.g. the behavior of PV generators. Highly accurate measurement equipment with a broad dynamic range is available for the measurements. To operate grid-connected power converters with a power rating of up to 1.25 MVA, voltages can be supplied in the laboratory over a wide range from 255 to 790 V. In addition, grid faults in the medium-voltage grid can be simulated to investigate dynamic grid support by power generators (Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT)).

We also offer our clients measurements in the field, for instance of large PV power plants. For this purpose, we have six measurement systems, each with 16 measurement channels, which can be distributed as required in the field. In our test field in Dürbheim, a flexibly configurable PV generator with a rated power of 1 MWp is available. It can be used for testing inverters under real world conditions. To this purpose, both low-voltage and medium-voltage connections are available.

Power-generating units can be tested according to international grid codes, e.g. for Germany, China or Great Britain. Highly accurate measurements of the efficiency of power electronic equipment can be made. We support our clients in modelling power-generating units, e.g. according to German TR4, and prepare dynamic simulation models of PV power plants or grid segments. We carry out customized measurement campaigns both in the laboratory and in the field. We advise our clients, also prior to such a measurement campaign, and offer accompanying simulations if required.

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Laboratory Equipment
- 1.4 MW DC source up to 1000 V / 1760 A or 2000 V / 880 A
- LVRT measurement unit up to 1 MVA
- Adjustable transformers (255 – 790 V / 1.25 MVA)
- 30 kW three-phase grid simulator

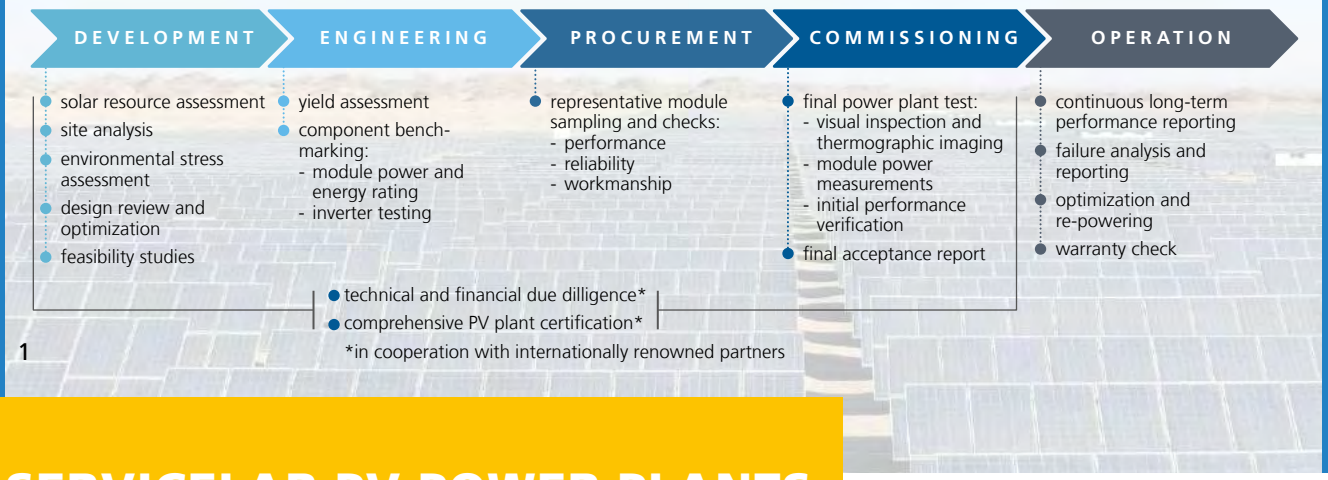
Test Field Equipment
- 1 MWp outdoor PV test field
- Mobile 4.5 MVA LVRT test container
- Adjustable transformers (264 – 1120 V / 1.25 MVA)

Measurement Equipment
- Highly accurate power analyzers
- 60 – 5000 A current converter

Simulation Software
- MATLAB®/Simulink®, PLECS®
- DIgSILENT PowerFactory

1 *High-current busbars (2500 A).*

2 *TestLab Power Electronics offers highly accurate characterization of grid-connected power electronics with respect to their behavior in the grid.*



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SERVICELAB PV POWER PLANTS

PHOTOVOLTAICS

PV power plants in the multi-megawatt range are becoming increasingly important internationally. Investors, project developers and EPCs (engineering, procurement, construction), banks and insurance companies must be sure that a power plant will deliver the predicted yield. With the Fraunhofer ISE quality cycle, we offer comprehensive quality assurance in all phases of a PV power plant project – from the development phase to on-going operation.

Already in the planning phase, we advise our clients on component selection and system design, taking the differing climatic conditions at each site into account. The results are also used for our internationally recognized yield predictions. With the help of testing programs developed in house, such as Quality Benchmarking and Procurement Checking, we investigate selected modules and components in our laboratories, TestLab and CalLab PV Modules, with respect to their quality and suitability for the planned application. This greatly reduces the risk of well-known fault mechanisms in advance.

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 and existing faults can be documented with the help of on-site analysis that includes visual inspection, thermography and determination of the actual power generated. 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 prediction. Early detection of sub-optimal operation enables power plant operators to take the necessary remedial steps as soon as possible.

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System Testing
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- "One-stop shop" for quality control
- Numerous reference projects around the world
- Consultancy and feasibility studies before project commencement
- Accurate and independent yield predictions
- Quality assessment and selection of project-specific components
- Technical testing and optimization of the entire system after commissioning
- Fault diagnosis of irregular operating performance
- Independent evaluation of power output and performance
- Optimization and re-powering of existing power plants
- Degradation analysis

1 *Quality control for all phases in the life cycle of a PV power plant.*

SERVICELAB BATTERIES

ENERGY SYSTEM TECHNOLOGY

In ServiceLab Batteries, we test battery cells, modules and complete battery systems based on lead-acid, NiMH and lithium-ion cells, as well as high-temperature batteries and double-layer capacitors. The laboratory with an area of 400 m² is equipped with battery testing systems and impedance spectrometers. We test either according to the test procedures specified by the relevant standards or in a climatic chamber or a water bath according to clients' specifications. We prepare electrical and thermal battery models, validated with data from our laboratory, which serve as the basis for system simulation and integration.

We offer long-term tests, lasting several months, of batteries and battery systems for durability investigations and lifetime analyzes. The cells and systems can be subjected to accelerated aging under exactly specified conditions. Our aging models allow the lifetime in a real application to be predicted.

A precision calorimeter is available for highly accurate investigations of the thermal behavior of battery cells. Among other possibilities, this allows the power loss occurring in the cell to be analyzed exactly and thus serves as a basis for developing optimal thermal management and optimizing the system dimensioning.

For the automotive sector, we test systems up to a power of 250 kW with currents up to 600 A and voltages up to 1000 V. The test systems can be controlled via a CAN bus.

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

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- Cell and system tests
- Long-term investigations
- Thermal investigations (calorimetry)
- System tests up to 250 kW
- Test rigs for home storage systems

1 *Test rig for long-term testing of battery storage units for residential PV systems.*

SERVICELAB SMART ENERGY

ENERGY SYSTEM TECHNOLOGY

As they become more economically attractive, distributed electricity generators, electric vehicles, heat pumps and electric storage units will be found in increasingly more residential buildings. At the same time, changes in the regulatory boundary conditions are resulting in completely new operating strategies, which are moving away from feeding all the generated electricity into the grid toward on-site consumption with control strategies which help to stabilize the local grid. ServiceLab Smart Energy is comprehensively equipped with the types of distributed generators and storage units that will be found in future residential buildings. This includes a simulator for electric loads to emulate triple-phase profiles with single-second accuracy and a PV simulator to provide IV-characteristics for inverters with 1 s resolution. The laboratory works with powerful simulation tools, which allow model-based "hardware-in-the-loop" operation to evaluate system controllers. This means that innovative system components such as PV-battery systems and heat pumps can be evaluated for any desired dynamic scenario of consumption and generation in the residential building context.

ServiceLab Smart Energy is equipped with the complete infrastructure needed to investigate questions concerning the system integration of distributed energy systems in a smart grid. System providers can thus test and evaluate both individual systems and also complete concepts in a realistic environment, such that business models and control strategies can be checked. These customized investigations include performance analyzes of novel electricity/heat supply systems in a realistic system environment, the evaluation of grid compatibility of distributed generator systems, the assessment of PV-battery systems with respect to efficiency and grid compatibility with the help of any required reference scenarios, the evaluation of thermal storage concepts with respect to distributed generation, the design and prototyping of intelligent operation management concepts and network-connected control systems, and the implementation of prototype systems with any type of interface.

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- Simulator for electric loads to emulate triple-phase profiles with 1 s accuracy
- PV simulator to provide IV characteristics with 1 s resolution for inverters
- Simulation of thermal load and solar thermal technology by computer-supported "hardware-in-the-loop" emulations
- Test rig for all common battery storage systems
- Network-connected charging stations for integration of electric vehicles into the domestic electricity circuit
- Evaluation of system performance compared to reference scenarios obtained by extensive monitoring

1 *Interior view of ServiceLab Smart Energy.*

SERVICELAB LIGHTING AND DC APPLIANCES

ENERGY SYSTEM TECHNOLOGY

For manufacturers, system integrators and users, we test, check and certify lamps, lighting systems and DC-powered consumer appliances corresponding to all common technology and configurations. Our equipment is designed specially to suit the requirements of off-grid power supplies and LED lighting systems in the small and medium power range. We can also measure grid-connected standard lamps and lights. The focus is always on the whole system, i.e. the power supply including the PV generator, electric storage units, electronics and electric loads such as lamps, TVs, radios, etc.

Characterization

We carry out accurate measurements of photometric and electric properties for DC lighting and power supply systems and their components. These include measurement of the luminous flux, the luminous efficacy and the illuminance distribution with the help of goniometric procedures, and investigations of the lighting and electric operating performance under different conditions, e.g. changes in the operating voltage and ambient temperature. We also determine the electrical properties of electronic controls, electronic ballasts and charge controllers, including the efficiency, self-consumption, operating performance, overload response and fault management.

Long-term Tests

For LED light sources and lamps equipped with LEDs, we determine the L70 and L50 lifetimes under various operating conditions. Using an automated test rig, we measure the achievable lighting duration (duration of autonomy) for battery-powered lamps and small systems.

Certification according to Different Testing Standards

We certify the quality of photovoltaically powered lighting systems according to IEC TS 62257-9-5 and IEC TS 62257-9-6 (Pico PV Systems and Solar Home System Kits). ServiceLab Lighting and DC Appliances is one of currently six testing laboratories around the world which have been accredited by Lighting Global for Solar Home System Kits. A special test rig for charge controllers allows them to be characterized up to 80 A and 150 V according to IEC 62509.

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- Software-controlled lighting measurement stand with a photometric integrating sphere of 1.50 m diameter
- Software-controlled spectrometer for automated measurement of the spectral distribution of light with a photometric integrating sphere of 1.0 m diameter
- Photogoniometer to determine the spatial luminosity distribution
- Long-term test stands to determine the L70 or L50 lifetime of LEDs and battery lifetimes
- Accurate broadband wattmeters, digital oscilloscopes
- Programmable, long-term stable power supplies
- Automated test rigs to determine autonomous lighting duration
- Automated test rigs to characterize electric storage units
- Partly automated test rig to characterize charge controllers, among other devices

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

SERVICELAB HEAT PUMPS AND CHILLERS

BUILDING ENERGY TECHNOLOGY

ServiceLab Heat Pumps and Chillers offers the most modern technology for developing, measuring and characterizing heat pumps and chillers, as well as their components. The modular test rig concept makes it feasible to test different types of technology and system configurations over a broad spectrum of operating conditions with different heat transfer media (air, water, brine). In addition to systems with an electric power supply of up to 50 kW, thermally driven equipment – heat, natural gas or a test gas – can be measured. The laboratory is equipped with an integrated safety concept which allows components and systems with flammable refrigerants or ammonia to be tested.

Test objects with heating or cooling power of up to 100 kW (50 kW in calorimetric operation) can be measured in a calorimetric double climatic chamber at temperatures between -25 °C and 50 °C and air humidity values between 25 % and 95 %. In addition, the laboratory also has several conditioning units for water and brine, which can provide the appropriate medium at temperatures from -25 °C to 95 °C in a power range up to 75 kW. In the three air-handling units, the air flow (80 m³/h to 5000 m³/h) can be conditioned in the temperature range from -15 °C to 50 °C and relative air humidity from 15 % to 95 %.

All measurement and conditioning equipment is suitable for measurements according to all relevant technical standards. Beyond this, we cooperate with our partners to develop individual measurement procedures, which enable efficient and cost-effective development and optimization of devices and more complex systems through realistic, dynamic measurement sequences, including "hardware in the loop".

Furthermore, component-specific test stands are designed and operated, where advanced measurement and analytical technology in the fields of fluid mechanics, acoustics, vibrations and gas analysis is used to address specific questions (e.g. particle image velocimetry (PIV), laser doppler anemometry (LDA), shadow-graphy and gas chromatography).

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- Design and development of components and systems using specialized software tools
- Specialized component test stands, e.g. for coolant distribution, evaporators or adsorbers
- Acoustic measurements in cooperation with Fraunhofer IBP
- Measurements according to EN 14511, EN 14825, EN 16147, EN 12309 and other standards
- Measurements according to VDI, EHPA, ErP, Eurovent and other standards and regulations
- Our staff is certified according to the F gas regulation, Class I.
- Accreditation according to ISO/IEC 17025 is planned for 2017.

1 *Equipment to measure the average air temperature and air humidity in the climatic chamber.*

SERVICELAB FUEL CELLS

HYDROGEN TECHNOLOGIES

ServiceLab Fuel Cells offers measurement services for manufacturers of fuel cell systems and components. We characterize and test membrane fuel cells and systems with an electric power rating of up to 20 kW_{el} in accordance with relevant standards.

Our characterization supports the design of stacks and systems and allows the operating strategy to be optimized for relevant application and operating conditions. Our walk-in climatic chamber allows fuel cell stacks and systems to be investigated for all climatic zones in the world. For investigations under conditions similar to those in systems, we can also control peripheral equipment such as pumps, ventilators or valves, without using the climatic chamber. Inhomogeneity in the stack is identified by simultaneous single-cell monitoring of the cell voltage and cell impedance spectrum.

We offer safety checks with respect to electrical safety and leakage. Additional characterization is possible to aid the selection of components and materials. We test single cells and cell components such as gas diffusion layers, electrodes and membranes according to recognized international test protocols. We measure both the performance and the long-term durability of the cell components. For in situ analysis, we are equipped not only to record current-voltage characteristics, but also to apply measurement procedures such as electrochemical impedance spectroscopy, cyclovoltammetry and linear-sweep voltammetry. As we are able to produce electrodes and membrane electrode assemblies, we are also able to investigate materials such as catalysts or catalyst substrates in situ.

In addition, we have access to a low-pressure chamber to simulate altitudes of up to 6000 m. We investigate cell components with respect to their electrochemical stability with a three-electrode configuration and exposure tests.

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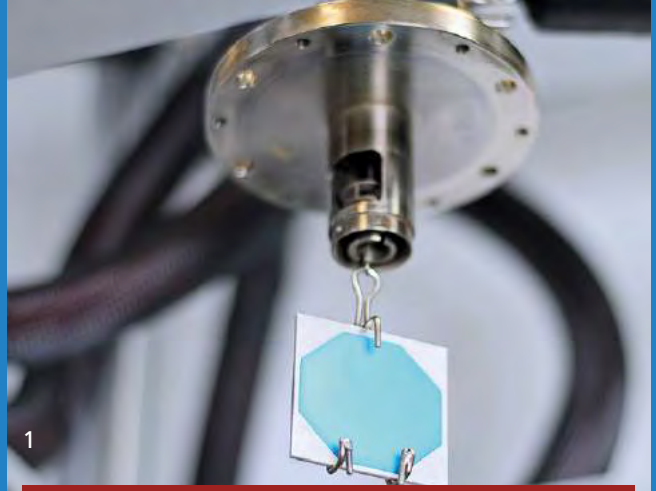
- Test rigs for fuel cell stacks up to 20 kW_{el} and 1000 ADC
- Test rigs for single cells and cell components
- On-line single-cell monitoring of fuel cell stacks with EIS, HFR and CV
- Insulation and short circuit tests for fuel cell stacks up to 5000 ADC
- Leakage tests of fuel cell stacks
- Climatic chamber with 8 m^3 interior volume and air flow rate up to 2000 Nm^3/h, temperatures from -50 °C to +80 °C, relative humidity from 10 % to 95 % (from +10 °C)
- Climatic chamber with 300 litres interior volume, temperatures from -40 °C to +95 °C, relative humidity from 10 % to 95 % (from +10 °C)
- Test of peripheral aggregates under hydrogen exposure and extreme climatic conditions
- Ex situ component tests of electrochemical long-term durability
- Analysis of contact resistances of materials – in-plane and through-plane

1 *Climatic chamber for temperatures from -40 °C to +80 °C and fuel cell test rig for power up to 20 kW_{el}, with connected single-cell monitoring unit based on electrochemical impedance spectroscopy.*



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SERVICELAB THERMOCHEMICAL AND POROUS MATERIALS

BUILDING ENERGY TECHNOLOGY

ServiceLab Thermochemical and Porous Materials offers a broad spectrum of analytical methods to characterize thermal conductivity, heat capacity, crystalline structure and surface groups. They are applied to analyze porous materials with regard to the internal surface area, pore structure, porosity, morphology and adsorption characteristics for different gases. Our facilities include equipment for gas sorption measurements with various test gases (N_2, CO_2, ethanol, methanol, H_2O) to determine adsorption characteristics.

- Volumetric and gravimetric sorption measurement instruments for a broad temperature range
- Diverse choice of gases, sample forms as well as measurement and analytical methods
- In situ XRD and FT-IR with humidity cycling
- Thermal conductivity from room temperature to 500 °C
- Hydrothermal stability tests up to 50,000 cycles
- Macro-pore characterization by mercury intrusion
- Helium pycnometry for density determination
- Calorimeters in different dimensions and temperature ranges
- Two laser flash systems
- Light and laser-scanning microscopy to determine particle form and size distribution, roughness and homogeneity of surfaces

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

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2

SERVICELAB PHASE CHANGE MATERIALS

BUILDING ENERGY TECHNOLOGY

We test and characterize phase-change materials (PCM), other thermal storage materials and heat transfer fluids from the materials level to the final product. In addition to materials characterization in our laboratories, we offer application-relevant investigations in test rigs. For example, an adiabatic test room is available which is used for the investigation of heating and cooling systems. We are recognized by the RAL Gütegemeinschaft PCM (PCM quality association) as a testing institute which is authorized to award the RAL PCM quality seal, which was developed by Fraunhofer ISE in cooperation with others for phase change materials and PCM products. ServiceLab Phase Change Materials offers complete certification by a single body.

- Certification acc. to RAL PCM quality seal, GZ 896
- Thermal characterization by heat-flux or Tian-Calvet DSC in the range from -90 °C to 800°C
- Characterization of macroscopic samples with an area of up to 50 cm x 50 cm with dynamic flat-plate equipment
- Determination of rheological behavior and viscosity by rotational rheometry in the temperature range from -20 °C to 600 °C
- Determination of thermal conductivity by xenon flash, laser flash and heating wire from – 50 °C to 1200 °C
- Determination of liquid density up to 100 °C
- Testing the thermal stability of PCM and PCM products under thermal cycling
- Field monitoring of PCM systems

2 *Equipment for thermal cycling of a wide variety of samples.*

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SERVICELAB AIR HANDLING UNITS

BUILDING ENERGY TECHNOLOGY

We investigate and characterize components and equipment for ventilation and air-conditioning. Three air-handling units are available, which cover a wide range of temperature, air humidity and flow rates. With their modular construction, the air-handling units can be combined as required for the relevant investigation. Operation of the test units in either a purely fresh-air input mode or with recirculation can be offered, with a zero-pressure measurement also being additionally possible. With special accessories, small test units on a centimeter scale can also be investigated with a greatly reduced air flow. Investigations relating to safety technology are carried out in a chamber which is equipped with a gas detection system and overflow extraction by suction. In addition, test units can also be connected to water or brine loops in the ServiceLab Heat Pumps and Chillers or installed in a climatic chamber and investigated there.

- Air flow ranges from 80 to 300 m³/h, 150 to 1000 m³/h, 800 to 5000 m³/h
- Heating power from 2 to 50 kW
- Cooling power from 2 to 15 kW
- Temperature range from -15 to 50°C
- Humidity range from 15 to 95 % r.h.
- Temperature tolerance ±0.3 K
- Humidification power range from 1 to 40 kg/h

3 *One of the three air-handling units in the ServiceLab.*

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SERVICELAB HEAT EXCHANGERS

BUILDING ENERGY TECHNOLOGY

The ServiceLab offers the infrastructure and scientific-technical know-how to characterize and evaluate heat exchangers for applications in energy technology in the lower power range (< 20 kW). The goal is to identify the potential to increase the efficiency of heat exchangers and make them useful in building technical applications such as electrically or thermally driven heat pumps, coolers or ventilation equipment. Different test rigs are available, with which both complete heat exchangers and individual components can be investigated with regard to their transfer properties (heat transfer, pressure drop) or detailed flow analysis. We draw on data from the technical literature and simulation tools for exact analysis of heat transport itself and restrictions to heat transport.

- Measurement of heat exchangers between air and various fluids (water, brine, coolants)
- Dimensions up to 1.5 x 1.5 m² (ribbed length / height)
- Measurement of characteristic structure segments (e.g. fin segments, fluid distribution)
- Measurement of dynamic/ stationary boiling and adsorption characteristics of water at low pressure on structure segments and heat exchangers
- High-resolution, optical flow analyzes
- Dimensioning and pilot construction of heat exchangers
- Application of simulation tools (CFD / FEM / heat exchanger design tools / system simulation software)

4 *Characterization of pressure loss and heat transfer for structure details of air-based heat exchangers.*

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28 PROJECTS IN THE "FRAUNHOFER-ZAYED" PROGRAM

In Abu Dhabi in January 2014, the Fraunhofer Institute for Solar Energy Systems ISE received the Zayed Future Energy Prize, which is awarded annually for trend-setting performance in the fields of renewable energy and sustainability. At the suggestion of the Institute Director, Prof. Eicke Weber, the prizemoney of 1.5 million US dollars was used for a funding program to support Fraunhofer project ideas for sustainable energy supply outside Germany. Often initiatives for international projects fail because of a lack of funds to initiate contacts, for initial visits or for the administrative effort to prepare proposals or quotes. The funding program is intended to provide support for these steps. The Executive Board of the Fraunhofer-Gesellschaft contributed further funding of equal value to the prizemoney, so that a program resulted with a total funding volume of 1.978 million euros.

To date, already the seventh call for proposals within the Fraunhofer-Zayed Program has been announced.
The 28 funded projects have already attracted research funding, including the required contribution from the applicant, with a value of around 1.75 million euros. Up to now, the Fraunhofer Institutes ICT, IFF, IKTS, IOSB, ISE, ISI, IWES and UMSICHT as well as the Fraunhofer Alliance for Energy have profited from projects in the Fraunhofer-Zayed Program.

All of the supported projects serve the preparation and acquisition of international projects in the fields of energy supply, energy conversion or energy utilization. The selection criteria for the projects supported in this framework include a knowledge gain (e.g. by the adaptation or development of new technology), development (as defined e.g. by the millennium development goals of the United Nations) and sustainability. Only projects with a high probability of research projects following from the initial funding were accepted in the program.

Most of the activity was directed towards Asia. 20 projects there were supported by the Zayed Program, particularly in India. Six (sub)projects each were funded in countries of South and Central America (Brazil, Columbia, Chile, Haiti) and of the MENA region. In most of the Zayed projects to date, the focus was on gaining a better understanding of the structures and demands of the local energy markets, making contacts and identifying funding options for concrete R&D projects.

1 *Within the Fraunhofer-Zayed Program, preliminary activities to prepare projects on quality assurance of solar-thermal systems in India were supported, among other initiatives.*

PRIZES AND AWARDS

Johannes Mayer
for the "Blue Inductive" spin-off project; admittance to the "30 under 30" Club in the "Industry" category, Forbes Magazine, February 2016

Heinrich Berg with Min Hsian Saw and Daniel Philipp
for the poster on "The Parasitic Capacity of a PV Module as the Cause of Increased Leakage Current and an Indicator for the Ingress of Moisture into the Encapsulation Material"; 2nd Prize in the Poster Awards 2016 at the 31st Symposium on Photovoltac Solar Energy from 8th to 11th March 2016, Bad Staffelstein, Germany

Friedemann Heinz, Dr Wilhelm Warta and Dr Martin Schubert
"SiliconPV Award" at the SiliconPV 2016 Conference on 9th March 2016 in Chambéry, France

Team from the Power Electronics Department headed by Prof. Bruno Burger and Cornelius Armbruster
for the development of an extremely compact and efficient inverter for the uninterruptible power supply (UPS) of electric devices; 2nd Prize of the "Stiftung Ewald Marquardt" for trend-setting developments in power electronics, March 2016 in Rietheim-Weilheim, Germany

Dr Ralf Preu and Dr Jan Nekarda
for work on a laser-based production process for high-efficiency solar cells; Joseph von Fraunhofer Prize 2016 at the Annual Conference of the Fraunhofer-Gesellschaft on 10th May 2016 in Essen, Germany

Monika Bosilj
for the poster on "Synthesis and Characterisation of Biomass-derived Carbons based on Hydrothermal Carbonisation" at the 7th International Symposium on Carbon for Catalysis – CarboCat VII, from 12th to 16th June 2016 in Strasbourg, France

Dr Frank Feldmann
for work on passivated contacts which enable a significant increase in efficiency for silicon solar cells; SolarWorld Junior Einstein Award at the Intersolar Europe Trade Exhibition on 22nd June 2016 in Munich, Germany

Prof. Eicke R. Weber
for contributions to materials research on defects in silicon and III-V semiconductors; Rudolf Jaeckel Prize 2016 of the German Vacuum Society at the "19. Arbeitstagung Angewandte Oberflächenanalytik" with the title "Surface meets Light", on 6th September 2016 in Soest, Germany

Thomas Lickert
2nd Prize for the best oral presentation on the topic of hydrogen and fuel cells at the 4th International Symposium on Innovative Materials for Processes in Energy Systems from 23rd to 26th October 2016, in Taormina, Italy

1 *In order to produce highly efficient PERC solar cells in series, Dr Jan Nekarda and Dr Ralf Preu (from left to right) developed the Laser-Fired Contact Process, for which they were awarded the Joseph von Fraunhofer Prize in 2016.*

2 *SolarWorld Junior Einstein Award 2016: (from left to right) Frank Asbeck, CEO of SolarWorld AG, the prizewinners Dr Frank Feldmann and Dr Udo Römer, and the chairman of the jury, Dr Holger Neuhaus.*

PROMOTING YOUNG RESEARCHERS AND ALUMNI RELATIONSHIPS

Qualification for Research and Industry

With its activities to promote young researchers and alumni relationships with former staff members, Fraunhofer ISE is exercising its corporate responsibility as the largest European research institute for solar energy. The goal is to support education and qualification for activities in the field of renewable energy and to encourage networking within the sector. Not only are numerous Bachelor, Master and doctoral theses completed each year at Fraunhofer ISE, but the Institute is also engaged in encouraging younger researchers. For example, Fraunhofer ISE has participated in the annual German "Girls' Day" for 15 years already. On this day, female school pupils from 5th grade on can become acquainted with apprenticeship trades and professions in science, technology, engineering and mathematics (STEM). In April 2016, 16 girls visited the solar research institute to talk with female scientists about their careers and professional activities, and carry out diverse experiments themselves.

So-called BOGY traineeships, which Fraunhofer ISE offers every year, are also very popular. Last year, six such traineeships were offered to high school pupils as an orientation guide for professions and study courses. In addition, we often offer guided tours at Fraunhofer ISE for visiting groups from universities, technical colleges, technical schools and general schools, usually as part of specific research and learning projects of the students.

A well-established project is the action, "Researchers as Guests in Schools", which is offered in cooperation with the "Solare Zukunft e.V.". Within this framework, scientists from the Institute visit school classes, conduct experiments together with the pupils and talk about their careers and their everyday experience as researchers.

Network in Industry and Research

"Fraunhofer ISE Alumni – Connected for a Solar Future" – this was the motto for an Internet platform directed toward former staff members, which the Institute founded in the summer of 2014. Since then, the alumni have been invited regularly to gatherings. An Institute history spanning more than 30 years, including completion of more than 300 doctoral theses and the foundation of 20 spin-off companies, provides the basis for fruitful alumni activities, and the number of alumni grows every year. By now, almost 150 persons are active on the Internet platform where they not only receive news from the Institute and the solar sector, but can also make and maintain connections within the group.

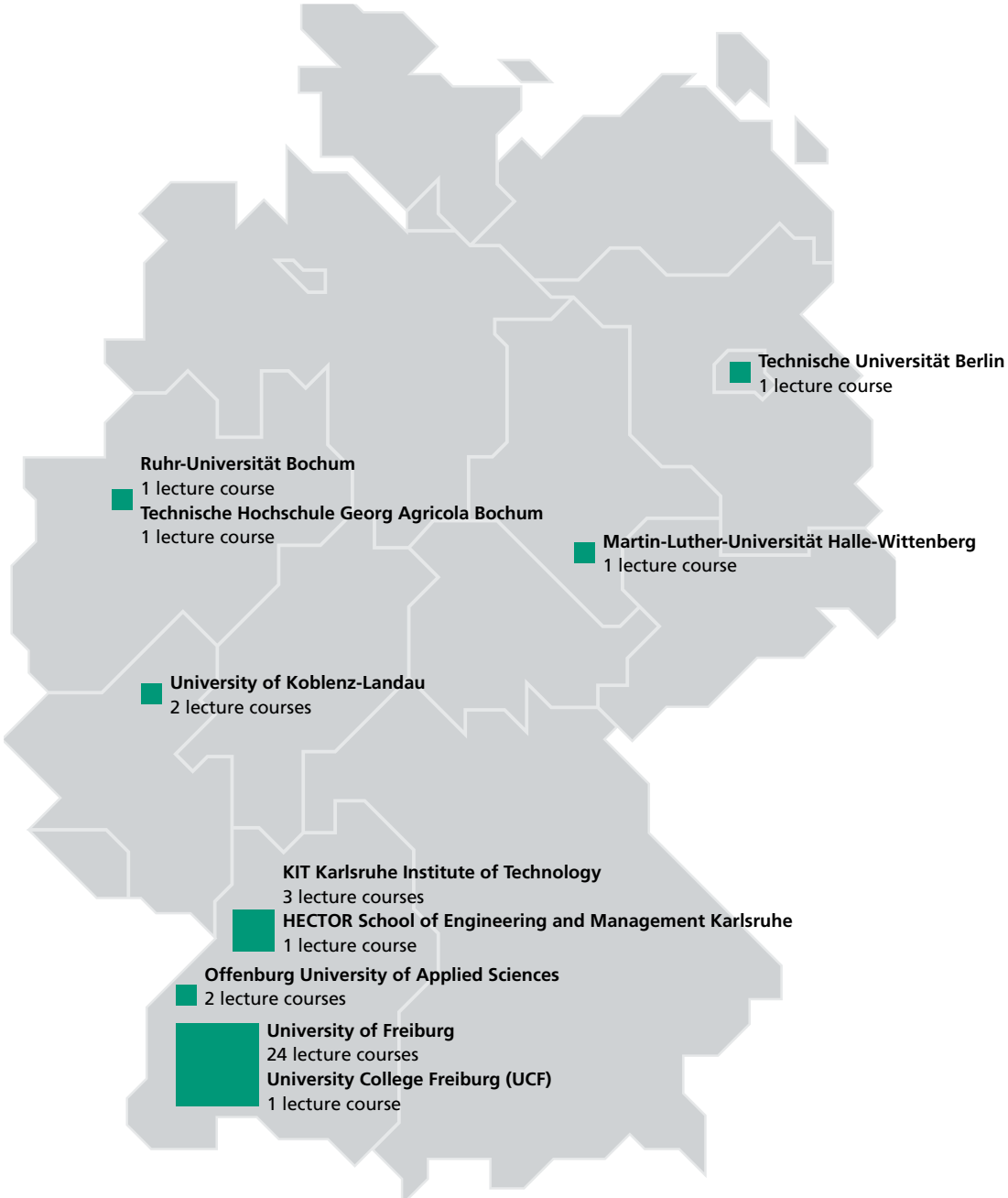
All of the other 1200 former staff members who are registered on the Fraunhofer ISE alumni address list profit from information and receive invitations to the alumni gatherings, which have now become well established. Last year, alumni events at the Energy Storage Conference in Düsseldorf and at Intersolar Europe and EU-PVSEC in Munich provided an opportunity for meeting and networking. In addition, an alumni meeting of the Fraunhofer-Gesellschaft in Berlin provided an opportunity for exchange beyond the Institute boundaries. Further people interested in the activities of the Alumni Network are sincerely welcome!

1 *On Girls' Day 2016, young visitors to the laboratories were able to carry out experiments themselves and thereby became better acquainted with technical fields of work.*

2 *At the Intersolar Europe in June 2016 in Munich, Fraunhofer ISE alumni were special guests at the event celebrating "30 years of CalLab PV Cells" held at the exhibition booth of Fraunhofer ISE.*

Fraunhofer ISE has close associations with universities, technical universities and other research institutions. Scientists from Fraunhofer ISE are involved in academic teaching at 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. A detailed overview of all lecture courses offered by the staff of Fraunhofer ISE can be found under: www.ise.fraunhofer.de/en/study-jobs-and-career/lecture-courses-seminars

LECTURE COURSES



PROFESSORSHIPS AND DOCTORAL THESES

PROFESSORSHIP

Prof. Werner Platzer
Honorary professor
Faculty of Environment and Natural Resources
University of Freiburg, appointed in March 2016

DOCTORAL THESES

Andreas Bachmaier
"Techno-ökonomische Strukturoptimierung von thermischen und elektrischen Energiespeichern in urbanen Energieversorgungssystemen auf Basis von Geoinformationen"
KIT Karlsruhe Institute of Technology, 2016

Sebastian Binder
"Aerosol Jet Printing – Contactless Deposition Technique for Solar Cell Metallization"
Ilmenau University of Technology, 2016

Martin Bivour
"Silicon Heterojunction Solar Cells Analysis and Basic Understanding"
University of Freiburg, 2016

Matthias Demant
"Quality Rating of Silicon Wafers – A Pattern Recognition Approach"
University of Freiburg, 2016

Jan-Bleicke Eggers
"Das kommunale Energiesystemmodell 'KomMod'"
Technische Universität Berlin, 2016

Fabian Fertig
"UMG Silicon and BOSCO Solar Cells"
University of Freiburg, 2016

Sebastian Gölz
"Feedback Seeking as an Active, Goal-Oriented Behaviour – A Psychological Reframing of Energy Consumption Feedback"
Philipps-Universität Marburg, 2016

Stefan Heckelmann
"Analyse zur Eignung von $Al_xGa_{1-x}As$ als aktives Material in III-V Mehrfachsolarzellen"
University of Konstanz, 2016

Friedemann Heinz
"Microscopic Photoluminescence Spectroscopy on Silicon"
University of Freiburg, 2016

Max Hendrichs
"Industrielle Metallisierungskonzepte für siliziumbasierte Rückkontaktsolarzellen"
Technische Universität Berlin, 2016

Hannes Höffler
"Lumineszenz-Imaging-Anwendungen in industrieller Fertigungsumgebung von Silicium-Solarzellen"
University of Freiburg, 2015

Mathias Kamp
"Electrochemical Processes for Metallization of Novel Silicon Solar Cells"
University of Freiburg, 2016

Tilmann E. Kuhn
"Design, Development and Testing of Innovative Solar-Control Facade Systems"
National and Kapodistrian University of Athens, Greece, 2016

Julia Kumm
"Entwicklung eines PVD-Metallisierungskonzeptes für industrielle Rückseitenpassivierte und -kontaktierte Siliciumsolarzellen"
University of Freiburg, 2016

Nena Milenkovic
"Kerfless Wafering: Porous Silicon Reorganization and Epitaxial Silicon Growth"
University of Konstanz, 2016

Anamaria Moldovan
"Ozonbasierte Reinigungs- und Konditionierungsverfahren für die Herstellung hocheffizienter Silizium Solarzellen"
University of Freiburg, 2016

Ralph Müller
"Ion Implantation for High-Efficiency Silicon Solar Cells"
University of Freiburg, 2016

Markus Mundus
"Ultrashort Laser Pulses for Electrical Characterization of Solar Cells"
University of Konstanz, 2016

Andreas Palzer
"Sektorübergreifende Modellierung und Optimierung eines zukünftigen deutschen Energiesystems unter Berücksichtigung von Energieeffizienzmaßnahmen im Gebäudesektor"
KIT Karlsruhe Institute of Technology, 2016

Thibault Pflug
"Evaluation of Façade Technologies with Switchable Thermal Properties"
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"Fluiddynamische Grundlagenmodellierung von Silizium-CVD-Anlagen"
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"Imaging and Thin-Film Optics of Organic Solar Cells"
University of Freiburg, 2016

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"Einseitige saure Ätzprozesse zur Herstellung von kristallinen Siliziumsolarzellen"
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Claudia Schmid
"Numerische Simulation und Optimierung der gerichteten Erstarrung von multikristallinem Silicium für die Photovoltaik"
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Tobias Schmid-Schirling
"Kombinierte Betrachtung von Optiken und Solarzelle für die konzentrierende Photovoltaik am Beispiel eines Parabolspiegels und einer Dreifachsolarzelle"
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"Analysis of Photonic Structures for Silicon Solar Cells"
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Nico Wöhrle
"Simulation und Verlustanalyse von local rückseitenkontaktierten Silicium-Solarzellen"
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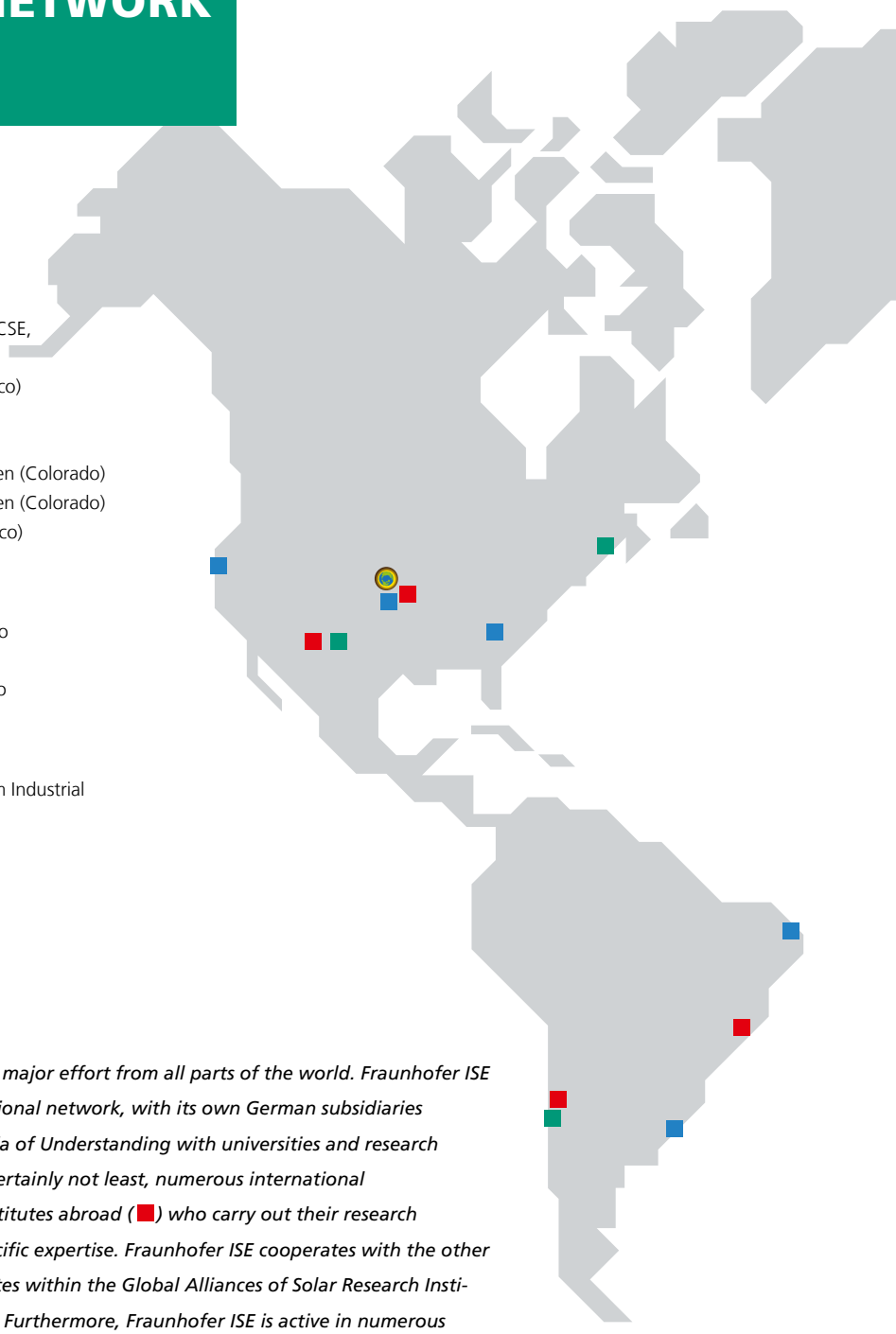
Dominik Wystrcil
"Ein Beitrag zur thermo-hydraulischen Optimierung niedrigexergetischer Wärme- und Kälteversorgungssysteme"
University of Freiburg, 2016

Verena Zipf
"Untersuchung von Schneckenwärmeübertragern in Latentwärmespeichern und Bewertung deren Einsatz in solarthermischen Energieerzeugungsanlagen"
Technische Universität Braunschweig, 2016

INTERNATIONAL NETWORK



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- Fraunhofer Center for Sustainable Energy Systems CSE, Boston (Massachusetts)
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- Georgia Institute of Technology, Atlanta (Georgia)
- Humboldt State University, Arcata (California)
- National Renewable Energy Laboratory NREL, Golden (Colorado)
- National Renewable Energy Laboratory NREL, Golden (Colorado)
- University of New Mexico, Albuquerque (New Mexico)

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- Energy International Centers of Excellence, Santiago

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  p. 76, Fig.1 and 2

EVENTS IN 2017 WITH PARTICIPATION OF FRAUNHOFER ISE

BAU Munich
Germany
16.-18.01.2017

Zukünftige Stromnetze für Erneuerbare Energien
OTTI, Berlin, Germany
31.01-01.02.2017

8th International Rechargeable Battery Expo
Tokyo, Japan
01.-03.03.2017

BIPV Symposium
Kloster Banz, Bad Staffelstein, Germany, 07.03.2017

Fachforum »Brandschutz und Wartung von PV-Anlagen«
Kloster Banz, Bad Staffelstein, Germany, 07.03.2017

Fachforum »PV-Diesel-Hybrid-Systeme«
Kloster Banz, Bad Staffelstein, Germany 07.03.2017

33. Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, Germany
08.-10.03.2017

Energy Storage / 11. Internationale Konferenz zur Speicherung Erneuerbarer Energien (IRES)
Düsseldorf, Germany
14.-16.03.2017

11. Entwicklerforum Akkutechnologien
Battery University Aschaffenburg, Germany
14.-16.03.2017

ISH Frankfurt
Germany
14.-18.03.2017

LOPEC International Exhibition and Conference for the Printed Electronics Industry
Munich, Germany
29.-30.03.2017

7th PV Performance Modeling and Monitoring Workshop
Lugano, Switzerland
30.03.17

SiliconPV, 7th International Conference on Crystalline Silicon Photovoltaics und PV Workshop
Freiburg, Germany
03.-05.04.2017

nPV Workshop
Freiburg, Germany
05.-06.04.2017

SOLAREX – Solar Energy and Technologies Fair
Istanbul, Turkey
06.-08.04.2017

11th SNEC PV POWER EXPO 2016
Shanghai, China
19.-21.04.2017

Hannover Messe Industrie
Hanover, Germany
24.-28.04.2017

13th International Conference on Concentrator Photovoltaics
(CPV-13)
Ottawa, Canada
01.-03.05.2017

Berliner Energietage
Germany
03.-04.05.2017

27. Symposium Thermische Solarenergie
Kloster Banz, Bad Staffelstein, Germany
10.-12.05.2017

Heat Pump Forum 2017
Brussels, Belgium
10.-12.05.2017

12th IEA Heat Pump Conference 2017
Rotterdam, Netherlands
15.-18.05.2017

PCIM Europe
Nuremberg, Germany
16.-18.05.2017

Power Electronics for Photovoltaics
Munich, Germany
29.-30.05.2017

Intersolar Europe / Electrical Energy Storage
Munich, Germany
31.05.-02.06.2017

KONGRESS-Forum ElektroMobilität
Berlin, Germany
01.-02.06.2017

44th IEEE Photovoltaic Specialists Conference
Portland, Oregon, USA
25.-30.06.2017

The Battery Show
Novi, Michigan, USA
12.-14.09.2017

33rd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)
Amsterdam, Netherlands
25.-29.09.2017

23rd SolarPACES Conference
Santiago de Chile, Chile
26.-29.09.2017

7th International Conference on Solar Air-Conditioning – PV Driven / Solar Thermal
Tarragona, Spain
28.-29.09.2017

13. SiliconFOREST Workshop
Feldberg-Falkau, Germany
08.-11.10.2017

World of Energy Solutions 2017 / f-cell 2017
Stuttgart, Germany
09.-11.10.2017

9. eCarTec
Munich, Germany
17.-19.10.2017

SHC 2017 Conference & ISES Solar World Congress
Abu Dhabi, United Arab Emirates
29.10.-2.11.2017

Solar-TEC
Cairo, Egypt
04.-06.12.2017