Fraunhofer

ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2017/18

Title page photo: Multi-junction solar cell of III-V semiconductors and silicon, which converts 33.3 % of solar radiation into electricity. By comparison, the best conventional silicon solar cells to date achieve an efficiency value of 26.7 %. The higher power is enabled by fifteen very thin III-V semiconductor layers, which have a total thickness of only 0.002 mm. The entire solar cell is approx. 0.25 mm thin. The III-V layers convert the visible part of the solar spectrum particularly efficiently. The longer-wavelength radiation penetrates the III-V layers and is absorbed in the silicon. The new cell is based on the dominating silicon solar cell technology, which commands more than 90 % of the global market. In fact, the two types of solar cell can hardly be distinguished from each other on the basis of outward appearance. At the same time, this new approach allows efficiency values to be reached which would be physically impossible with a simple silicon solar cell.

FOREWORD

The Institute Directors Dr Andreas Bett (left) and Prof. Hans-Martin Henning (right).

The past year began with a change in leadership and a new dual-director structure that complements the broad range of R&D themes and large size of Fraunhofer ISE. Since January 2017, Fraunhofer ISE has two institute directors for the first time, whereby each of us is responsible for one of the two main research themes that define the strategic direction of the institute. As joint leaders, we consult constantly with each other. We view and represent the institute as one unit, as there are strong interdependencies between the two main themes. Andreas Bett is responsible for photovoltaics, which is a main pillar of a future sustainable energy system. Closely correlated with this theme are the many topics of energy technology and systems, which are the focus of Hans-Martin Henning. Derived on the basis of this concept of Fraunhofer ISE, we spent the past one and a half years undergoing a restructuring process and have successfully established a new organizational structure in 2017 which is to lead the Institute into the future. In addition to the thematic orientation defined by the two large divisions, namely "Photovoltaics" and "Energy Technologies and Systems", we also restructured the organizational units within each division to better meet the challenges of the energy transformation and the needs of our customers.

The Division of Photovoltaics experienced an incisive event at the beginning of 2017: The main laboratory of PV-TEC – Photovoltaic Technology Evaluation Center was almost completely destroyed by fire. Since 2006, PV-TEC has served as a globally unique and extremely successful research platform for production technology for solar cell manufacturing. We are working vigorously to rebuild PV-TEC so that we can again offer the full range of services to our industry customers as soon as possible. During reconstruction, we were able to relocate some work to other laboratories in order to continue projects albeit with some time delay. As institute directors, we would explicitly like to extend our sincere thanks to all of the people who helped extinguish the fire, carry out the clean-up and rebuild the lab. This also includes the many expressions of sympathy and offers of assistance that we received immediately after the fire. We are pleased to announce that PV-TEC will reopen in spring 2018.

Despite this unexpected incident, 2017 was again a very successful year for Fraunhofer ISE. In photovoltaics, we were able to achieve several new records for solar cell efficiencies; for example, a 22.3 percent world record efficiency for multicrystalline silicon solar cells and 25.7 percent for monocrystalline silicon solar cells with TOPCon technology. With our monolithic tandem approach on silicon we aimed to surpass the theoretical efficiency for silicon material of 29.4 percent. We achieved this success with our first prototypes reaching an efficiency of 33.3 percent. This is an important first step for the further technological development of photovoltaics that we will continue in the new laboratory center "Center for High Efficiency Solar Cells", which is on its way. The foundation stone was laid in fall 2017 and construction will be completed in 2019. We extend our thanks to the Federal Government and the State of Baden-Württemberg for funding this new laboratory. In October 2017, the Fraunhofer Center for Silicon Photovoltaics CSP, a joint facility of Fraunhofer ISE and Fraunhofer IMWS in Halle an der Saale, celebrated its tenth anniversary.

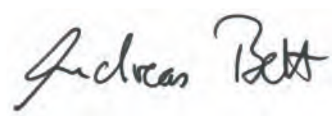
In 2017, the Division of Energy Technologies and Systems also had many notable achievements. These include successful developments in the compact construction of inverters as well as the creation of a powerful energy monitoring platform for buildings that is universally applicable. An agrophotovoltaic project, based on an early idea of the Institute's founder Prof. Adolf Goetzberger, successfully completed its first year of operation. Results of the first agrophotovoltaic harvest showed a land use optimization of 60 percent through the combined production of electricity and agricultural crops. In the business area Hydrogen Technologies, an important milestone was achieved: A Power-to-Gas system which feeds hydrogen, generated by water electrolysis, into the natural gas grid was put into operation.

In November, the German scientific academies acatech, Leopoldina and the Union of Germany Scientific Academies published a position paper called "Sector Coupling – Options for the Next Phase of the Energy Transformation". The key findings are based on calculations made with "REMod", a simulation program developed at Fraunhofer ISE to carry out detailed analyses on development paths for entire energy systems. The study was conducted in the working group Sector Coupling within the project Energy Systems of the Future (ESYS) under the joint leadership of Hans-Martin Henning and Eberhard Umbach, presidium member of acatech. The results of this study confirm our own results on energy-relevant technologies for the energy transformation and reinforce the strategic decisions we made for the Division of Energy Technologies and Systems that will come to fruition in 2018. We also decided to expand our efforts in battery research and have established the Department of Electrical Energy Storage. In addition to battery testing and system development, we will also build up research in the field of battery cell production.

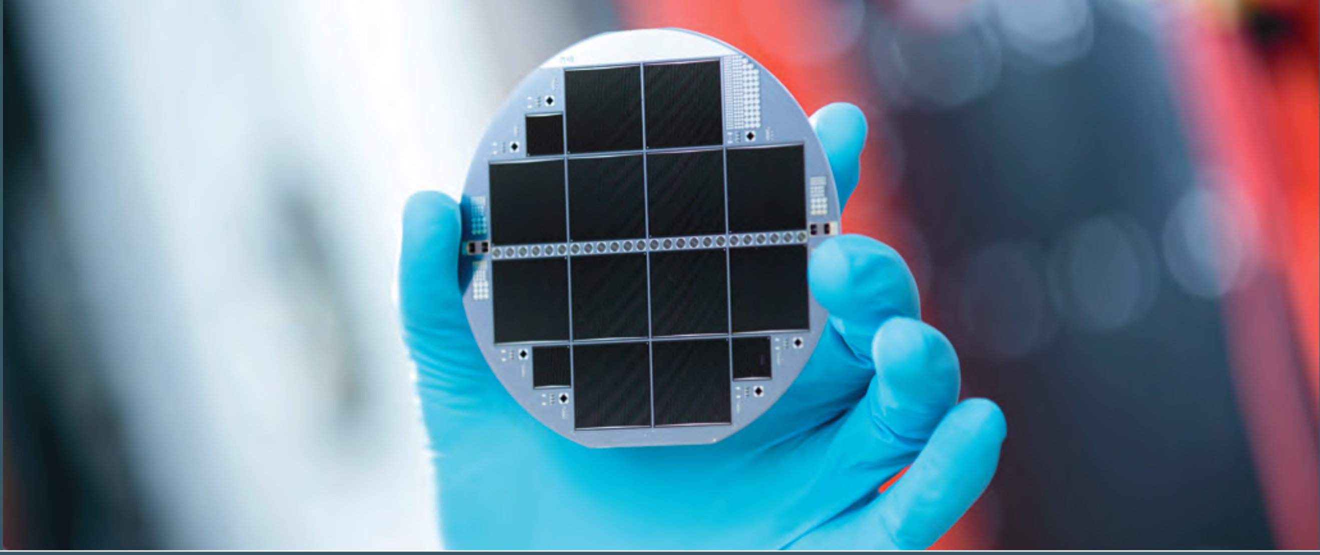
Here our acquired expertise in materials, processes and production technology in photovoltaics will benefit us greatly. Another strategic focus is power electronics. In 2018, we will open a new, efficient multimegawatt laboratory which enables us to test and develop high-performance electronics, a key factor for maintaining grid stability in an energy supply system strongly based on fluctuating energy sources.

Strategy audits provide important information for the strategic direction of R&D at Fraunhofer ISE. In 2017, hydrogen technology underwent an audit. In 2018, photovoltaics will be audited.

For the support and funding of Fraunhofer ISE and for the excellent cooperation, we warmly thank the Board of Trustees, auditors, scholarship donors, our contact partners and sponsors in the Ministries on the federal and state levels as well as the funding bodies and our project partners. We look forward to exciting years ahead in which, together with our partners, we forge ahead to advance the energy transformation in Germany and worldwide and ultimately to achieve a future energy supply based on renewable energy sources.



Prof. Hans-Martin Henning Dr Andreas Bett



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 strengths 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 Vision

The 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 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 own 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

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ORGANIZATIONAL STRUCTURE

From left to right: Prof. Hans-Martin Henning, Dr Harry Wirth, Dr Andreas Bett, Dr Olivier Stalter, Dr Ralf Preu, Karin Schneider, Prof. Stefan Glunz, Dr Christopher Hebling, Dr Sonja Reidel, Jochen Vetter, Dr Peter Schossig.

The organizational structure of Fraunhofer ISE is defined, apart from Business Administration, Facility Management and staff units, by the two scientific Divisions, "Photovoltaics", and "Energy Technology and Systems".

In addition, we operate with market-oriented business areas for external representation:

Photovoltaics

- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Emerging Photovoltaic Technologies
- Photovoltaic Modules and Power Plants

Energy Technology and Systems

- Solar Thermal Technology
- Building Energy Technology
- Hydrogen Technologies
- Energy Systems Technology

Fraunhofer ISE is supported by long-standing mentors and experts in the solar energy sector as consultants: Prof. Adolf Goetzberger (founder of the Institute and Institute Director 1981 – 1993), Prof. Joachim Luther (Institute Director 1993 – 2006), Prof. Volker Wittwer (Deputy Institute Director 1997 – 2009) and Prof. Eicke R. Weber (Institute Director 2006 – 2016).

Institute Directors

Prof. Hans-Martin Henning | Phone: +49 761 4588-5134
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Press and Public Relations

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BOARD OF TRUSTEES

The Board of Trustees assesses the research projects and advises the Institute Directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the work programme of Fraunhofer ISE (Status: 31st December 2017).

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 72 institutes and research units. The majority of the more than 25 000 staff are qualified scientists and engineers, who work with an annual research budget of 2.3 billion euros. Of this sum, almost 2 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state 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 – 1 826), the illustrious Munich researcher, inventor and entrepreneur.

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

EXTERNAL BRANCHES, COOPERATION, NETWORKS

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In addition to its headquarters in Freiburg, Fraunhofer ISE has three external branches – one of them operated jointly with the Fraunhofer Institute for Microstructure of Materials and Systems IMWS in Halle, another with the Fraunhofer Institute for Integrated Systems and Device Technology IISB in Freiberg. The institute is directly involved in specific collaboration with two international bodies and holds Memoranda of Understanding with around 40 research institutes around the world. Among other memberships, it is a member of the German ForschungsVerbund Erneuerbare Energien (FVEE – Research Association for Renewable Energy) and the Association of European Renewable Energy Research Centres (EUREC). Fraunhofer ISE, the National Renewable Energy Laboratory NREL in USA and the National Institute of Advanced Industrial Science and Technology AIST in Japan together form the Global Alliance of Solar Research Institutes (GA-SERI).

Fraunhofer ISE's External Branches

- Fraunhofer ISE Laboratory and Service Center, Gelsenkirchen LSC: production-relevant process development of thin-film silicon solar cells, silicon hetero-junction solar cells and multicrystalline silicon solar cells
- Fraunhofer Center for Silicon Photovoltaics CSP, Halle/Saale: crystallization technology (CSP-LKT), recycling of PV modules
- Fraunhofer Technology Center for Semiconductor Materials THM, Freiberg: production of crystalline materials and the mechanical separation of the produced raw material

International Cooperation

- Fraunhofer Center for Sustainable Energy Systems CSE, Boston, USA and CFV Solar Test Laboratory, Albuquerque, New Mexico
- Fraunhofer Chile Research – Centro para Tecnologías en Energía Solar (FCR-CSET), Santiago, Chile: solar generation of electricity, water purification and process heat

Fraunhofer Energy Alliance

Fraunhofer ISE is not only one of currently 18 members of the Fraunhofer Energy Alliance, but has also been responsible for its management since its establishment in 2003. In December 2016, the Institute Director, Prof. Hans-Martin Henning, was elected as the new Speaker of the Alliance. As one of the largest energy research associations in Europe, the Fraunhofer Alliance for Energy offers R&D services in the fields of renewable energy, storage technology, energy efficiency and components and concepts for systems, buildings and neighbourhoods.

Further Networking within the Fraunhofer-Gesellschaft

- Fraunhofer Alliances: Batteries, Building Innovation, Nanotechnology, Space, 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"

Sustainability Center in Freiburg

The trans-disciplinary research network was founded in 2015 and consists of the University of Freiburg and the five Fraunhofer Institutes located in Freiburg. The focus is on research and teaching on sustainability topics and the development of innovative products and services together with regional enterprises. The engineering core of the Sustainability Center is provided by the "Institut für Nachhaltigkeit und Technische Systeme" (INATECH – Institute for Sustainability and Technical Systems), which addresses sustainable materials, energy systems and resilience.

1 *Fraunhofer CSP in Halle/Saale celebrated its 10th anniversary on 25.10.2017. © Fraunhofer CSP*

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 1200.

The Fraunhofer Institute for Solar Energy Systems ISE is committed to promoting energy supply systems which are based on renewable energy sources and are sustainable, economic, safe and socially just. Within its research focusing on energy efficiency, energy conversion, energy distribution and energy storage, it creates technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. Parallel to a funding base from the Fraunhofer-Gesellschaft, the Institute finances itself to 85 percent with contracts for applied research, development and high-technology services. Fraunhofer ISE is certified according to DIN EN ISO 9001:2008.

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. The Institute also offers testing and certification services in its seven accredited test and calibration laboratories. The basis for the research and development activities of Fraunhofer ISE is modern technical infrastructure which is divided into R&D Centers for more fundamental research and production-relevant Technology Evaluation Centers.

Business Areas

The two large organizational divisions of Fraunhofer ISE – for Photovoltaics, and Energy Technology and Systems – address five market-oriented business areas.

Photovoltaics

- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Emerging Photovoltaic Technologies
- Photovoltaic Modules and Power Plants

Solar Thermal Technology

- Materials Research and Optics
- Thermal Collectors and Components
- Thermal Systems Engineering
- Thermal Storage for Power Plants and Industry
- Water Treatment

Building Energy Technology

- Building Envelope
- Heating and Cooling Technologies
- Energy Concepts and Building Performance Optimization
- Thermal Storage for Buildings
- Materials and Components for Heat Transformation

Hydrogen Technologies

- Thermochemical Processes
- Hydrogen Production by Water Electrolysis
- Fuel Cell Systems

Energy Systems Technology

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

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R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of 15 700 m^2 and extremely modern equipment and facilities are the basis for our competence in research and development. The R&D infrastructure of Fraunhofer ISE is divided into eight Laboratory Centers and four production-relevant Technological Evaluation Centers:

- » Center for High Efficiency Solar Cells
- » Center for Emerging PV Technologies
- » Center for Optics and Surface Science
- » Center for Material Characterization and Durability Analysis
- » Center for Heating and Cooling Technology
- » Center for Energy Storage Technologies and Systems
- » Center for Power Electronics and Sustainable Grids
- » Center for Fuel Cells, Electrolysis and Synthetic Fuels
- » SiM-TEC – Silicon Materials Technology Evaluation Center
- » PV-TEC – Photovoltaic Technology Evaluation Center
- » Module-TEC – Module Technology Evaluation Center
- » Con-TEC – Concentrator Technology Evaluation Center

Services in Accredited Laboratories

In addition, Fraunhofer ISE offers independent testing and certification services. Complementing its research and development centers, the Institute has seven calibration and test laboratories which are accredited. With their specific measurement and testing equipment, they offer services for commercial enterprises and scientific institutions:

- » CalLab PV Cells
- » CalLab PV Modules
- » TestLab PV Modules
- » TestLab Solar Façades
- » TestLab Solar Thermal Systems
- » TestLab Power Electronics
- » TestLab Heat Pumps and Chillers

Spectrum of activities

In its research activities, Fraunhofer ISE develops new products, processes or services and optimizes 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, particularly small and medium-sized enterprises without their own large R&D department gain access to high-performance laboratory infrastructure and excellent research services.

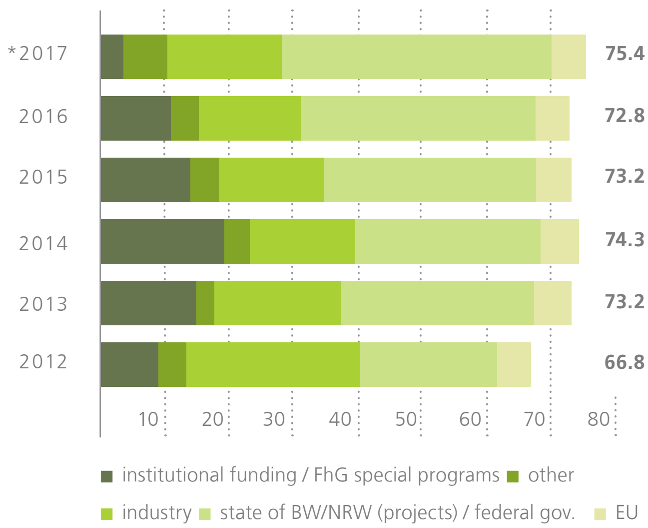
The Institute carries out research and development projects at various phases in the life cycle of a given technology. Depending on the task and requirements of our clients and the technological readiness level of the topic, the Institute offers services in various forms:

- » New material / process
- » Prototype / pilot series
- » Patent / licence
- » Software / application
- » Analysis based on measurement technology / quality control
- » Advice / planning / studies
- » Services (measurement, testing, monitoring)

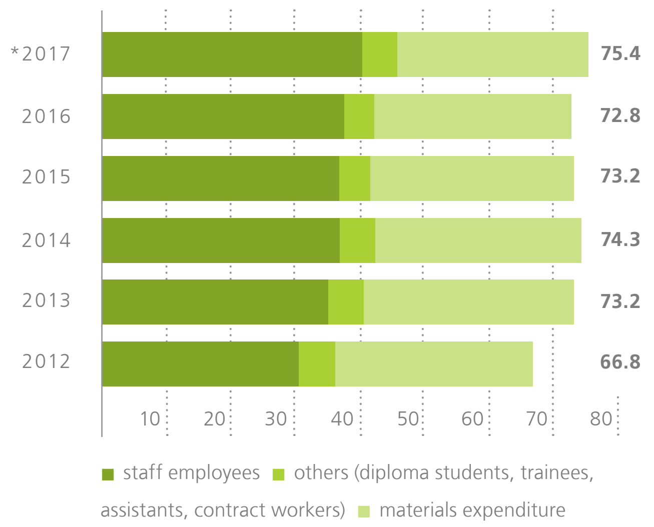
1 *Main building of Fraunhofer ISE in Freiburg.*

THE INSTITUTE IN FIGURES

Expenditure million euros**

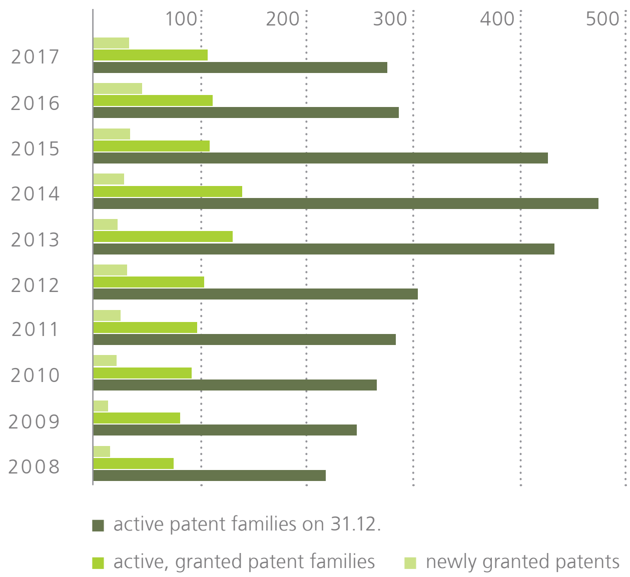


Income million euros **

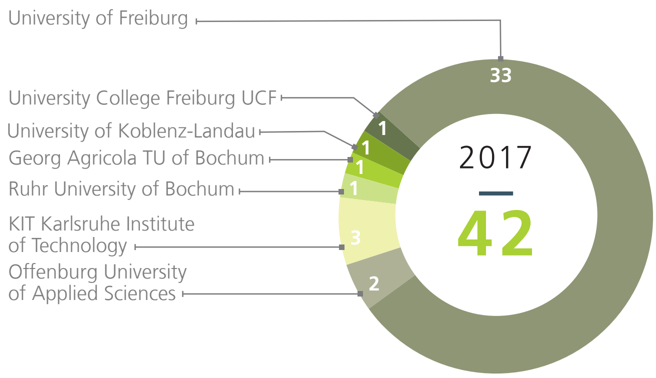


*preliminary **without investments – the total budget 2017 (incl. investments) totaled 89.4 million euros.

Patents

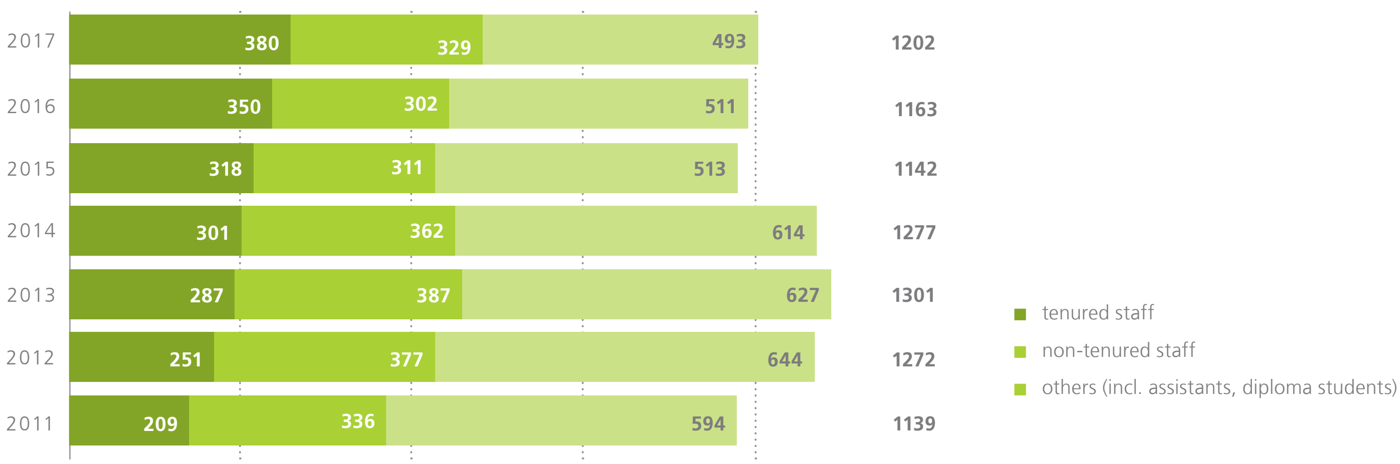


Lecture Courses and Seminars

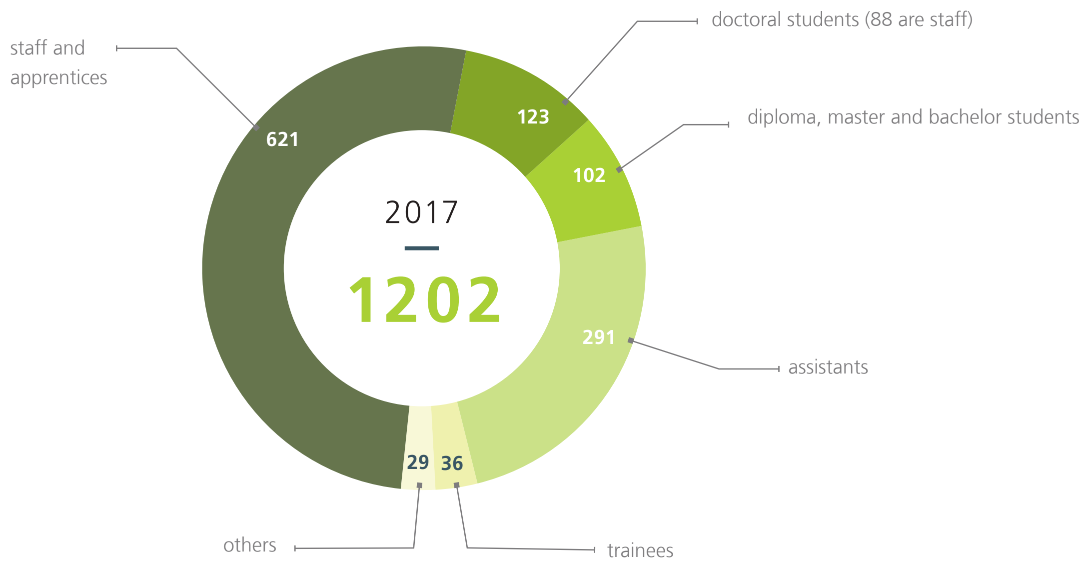


32 scientists of Fraunhofer ISE give regular lectures at universities in addition to their research work.

Personnel



Personnel 2017



DOCTORAL THESES

Karolina Baltins
"Global Assessment of Environmental Stress Factors for Solar Technology Applications Using Geographical Information Systems"
University of Freiburg, 2017

Kilian Dallmer-Zerbe
"Probabilistische Planung von Verteilnetzen unter Berücksichtigung von dezentralen Energieanlagen"
Technical University of Dresden, 2017

Johannes Eisenlohr
"Light Trapping in High-Efficiency Crystalline Silicon Solar Cells"
University of Konstanz, 2017

Karoline Fath
"Potential for Photovoltaic Systems on Buildings in Germany"
Karlsruhe Institute of Technology (KIT), 2017

Stefan Feuerhahn
"Analysis and Evaluation of the IEC 61850 Communication Standard for Monitoring and Control of Distributed Energy Resources"
Technical University of Dortmund, 2017

David Fischer
"Integrating Heat Pumps into Smart Grids – A Study on System Design, Controls and Operation"
KTH Royal Institute of Technology, Stockholm, Sweden, 2017

Dominik Fröhlich
"Structural and Stability Investigations of Metal-Organic Frameworks under Humid Conditions for Heat Transformation Applications"
Heinrich Heine University Düsseldorf, 2017

Ino Geisemeyer
"Characterization of Crystalline Silicon Solar Cells under Realistic Operating Conditions"
University of Konstanz, 2017

Bishal Kafle
"Mask-less Dry Texturing of Crystalline Silicon Solar Cells in Atmospheric Pressure Conditions"
University of Freiburg, 2017

Sven Killinger
"Anlagenscharfe Simulation der PV-Leistung basierend auf Referenzmessungen und Geodaten"
Karlsruhe Institute of Technology (KIT), 2017

Konstantin Klein
"Quantifying the Energy Flexibility of Building Energy Systems: Evaluation of Grid-supportive Concepts for Space Heating and Cooling in Non-residential Buildings"
Karlsruhe Institute of Technology (KIT), 2017

Karin Krauß
"Multicrystalline Silicon Solar Cell Concepts and Light-induced Degradation"
University of Freiburg, 2017

Saskia Kühnhold-Pospischil
"Oberflächen-Passivierung von kristallinem Silicium durch Aluminiumoxid"
University of Freiburg, 2017

Martin Lieder
"Metallstrukturierung und Dotierung mit Elementen der III.-Hauptgruppe auf Siliziumsubstraten mit Hilfe von Laser-chemischen Prozessen"
University of Freiburg, 2017

Andreas Lorenz
"Evaluierung von Rotationsdruckverfahren für die Metallisierung von Silicium-Solarzellen"
University of Freiburg, 2017

Thomas Mißbach
"Entwicklung eines Lichtmodulator-basierten Messsystems zur Bestimmung der externen Quanteneffizienz von Mehrfachsolarzellen"
Karlsruhe Institute of Technology (KIT), 2017

Tim Niewelt
"Lifetime-limiting Defects in Monocrystalline Silicon"
University of Freiburg, 2017

Maximilian Pospischil
"Entwicklung eines Dispensiersystems mit Paralleldruckkopf zur kontaktlosen Vorderseitenmetallisierung von Siliciumwafern im industriellen Maßstab"
University of Freiburg, 2017

Sarah Röttinger
"Organic Solar Cells Based on Vacuum Processed Small Molecules – Device Characteristics, Processing and Stability Aspects"
University of Freiburg, 2017

Ammar Salman
"Blindleistungs-Spannungsregelung zur optimierten Einbindung dezentraler Energieerzeugungsanlagen in das Stromnetz"
University of Kassel, 2017

Bernd Steinhauser
"Passivating Dopant Sources for High-Efficiency n-type Silicon Solar Cells"
University of Konstanz, 2017

Heiko Steinkemper
"Numerical Simulation of Silicon Solar Cells"
University of Konstanz, 2017

Charlotte Weiss
"New Silicon Nanocrystal Materials for Photovoltaic Applications"
Friedrich-Schiller University Jena, 2017

PRIZES AND AWARDS

Sönke Rogalla, Stefan Schönberger, Patrick Hercegfi, Benjamin Stickan | 1st poster prize for "NETfficient – Hochkompakter und modularer Batterieumrichter für zukünftige Smart Grids und Industrienetze" at the Symposium Photovoltaische Solarenergie, 8th – 10th March 2017, Bad Staffelstein, Germany

Robin White | "Young Researcher Award 2017" from the Global Green Chemistry Centres (G2C2)

Monika Bosilj | Poster prize for "Hydrothermal Carbons & their Derivatives in Heterogeneous Catalysis" at the 1st International Conference on Hydrothermal Carbonisation, 3rd – 4th April 2017, London, Great Britain

Wolfram Kwapil | SiliconPV Award for "Kinetics of Carrier-Induced Degradation at Elevated Temperature in Multicrystalline Silicon Solar Cells" at the 7th SiliconPV, 3rd – 5th April 2017, Freiburg, Germany

Armin Richter | SiliconPV Award for "Silicon Solar Cells with Passivated Rear Contacts: Influence of Wafer Resistivity and Thickness" at the 7th SiliconPV, 3rd – 5th April 2017, Freiburg, Germany

Jens Ohlmann | Best Poster Award for "35.1 % Efficient GaInP/GaInAs Dual-Junction Solar Cells Optimized for Direct Hydrogen Generation", 26th June 2017 at the 44th IEEE Photovoltaic Specialists Conference, Washington DC, USA

Romain Cariou | Best Poster Award for "Wafer Bonded III-V on Silicon Multi-Junction Cell with Efficiency beyond 31 %", 29th June 2017 at the 44th IEEE Photovoltaic Specialists Conference, Washington DC, USA

Sven Killinger | Best Student Poster Award for "Evaluating Different Upscaling Approaches to Derive the Actual Power of Distributed PV Systems", 29th June 2017 at the 44th IEEE Photovoltaic Specialists Conference, Washington DC, USA

Anne-Christine Scherzer | Poster Award for "Spatially Resolved Analysis of the Characteristic Time Constant of the Low-Frequency Arc in Electrochemical Impedance Spectra of PEMFC" July 2nd – 5th 2017 at the "647. WE-Heraeus-Seminar on Next Generation PEM Fuel Cells", Bad Honnef, Germany

Jakob Hömberg | Dr Tyczka Energy Prize for the M.Sc. thesis, "Lifecycle Assessment of Methanol Production Based on Renewable Hydrogen and Recycled Carbon Dioxide (Power-to-Methanol)", 14th September 2017, Geretsried, Germany

Katharina Gensowski | EU PVSEC Poster Award for "Development for Electrochemical Screen Printing to Structure Metal Layers of Back Contact Solar Cells" at the 33rd EU PVSEC, 25th – 29th September 2017, Amsterdam, Netherlands

Rok Kimovec | EU PVSEC Student Award for the joint paper, "Multi-segment Photovoltaic Laser Power Converters and their Electrical Losses", at the 33rd EU PVSEC, 25th – 29th September 2017, Amsterdam, Netherlands

Sven Killinger, Nicholas Engerer, Björn Müller | "Best Paper in Solar Resources / Meteorology", Prize of the "Solar Energy" journal for the joint paper, "QCPV: A Quality Control Algorithm for Distributed Photovoltaic Array Power Output", ISES Solar World Congress 2017, 29th October – 2nd November 2017, Abu Dhabi, United Arab Emirates

Thibault Pflug | Kepler Prize of the Saint Thomas Foundation for the Ph.D. thesis "Development, Characterization and Evaluation of Switchable Façade Elements", November 2017, INSA Strasbourg, France

Mohamed Ouda and Christoph Hank | Poster prize of the Stiftung Energie & Klimaschutz BW for "Using Renewable Energy for Thermochemical Catalytic Synthesis of Sustainable Designer Fuels" in the concept competition, »Meine Stadt von morgen«, November 2017

SUSTAINABILITY

www.ise.fraunhofer.de/en/about-us/sustainability.html

The development of problem-solving approaches and decision bases for particularly important societal challenges represent essential contributions of science to sustainable development. Fraunhofer ISE makes a contribution with most of its research and development work toward reaching the "Sustainable Development Goals" of the United Nations. These development goals for international sustainability policy were defined by the United Nations in 2015 and should be implemented throughout the world by 2030.

The essential contribution of Fraunhofer ISE is in the form of scientific-technological developments toward the seventh development goal, "Affordable and Clean Energy". Beyond this one, we have identified seven further development goals which are relevant for the work within our research portfolio.

As debates about the development of the energy transformation in Germany demonstrate, the involvement of all actors participating in the innovation process at the interface between science, economics and society is playing an increasingly important role. Under the motto, "Participative Technology Planning", the innovation planning in the "APV-Resola" project, funded by the German Federal Ministry of Education and Research (BMBF), Fraunhofer ISE included citizens' workshops, for example, to orient the innovation planning toward current needs of society. This should facilitate the process of embedding APV systems technology in society.

Challenges to society like the energy transformation are distinguished not only by the diversity of actors involved but also by great complexity, interconnection and open questions. Beyond technological development, a core competence of Fraunhofer ISE is in transferring technical solutions to applications-oriented system innovations. Thus, we are preparing innovative solutions to meet the challenges of the energy transformation, from the initial phase of fundamental research approaches through to application-oriented research

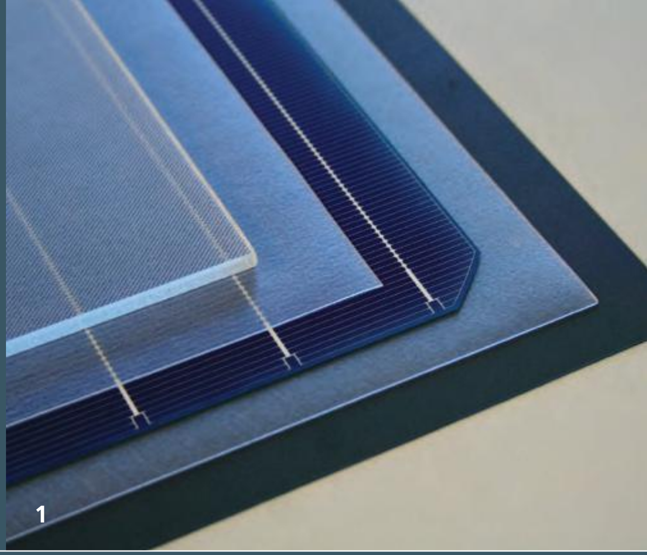
Graph: Relationships of the "Sustainable Development Goals" to the topics addressed by Fraunhofer ISE.

and market integration, both in depth within individual disciplines and also on an interdisciplinary and trans-systemic basis. As a result, our technological developments and services are applied in holistic energy, urban and/or mobility systems.

In addition to our research contributions for a sustainable energy supply, we also pursue the goals of integrating our social and ecological responsibility into our organizational processes and developing our social responsibility further in the form of Corporate Responsibility.

We report on our sustainability content and measures according to the guidelines of the "Global Reporting Initiative". In 2017, Fraunhofer submitted a declaration of compliance with the German Sustainability Code for the first time.

PARTNER OF THE INDUSTRY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Innovations offer the basis for both a successful economy and successful companies. An appropriate and often extensive technical infrastructure and experienced professionals are needed, however, in order to help transform ideas into innovations, and ultimately, into successful products on the market. Cooperation with research facilities offering the cutting-edge in science and research can provide this assistance.

Contract research is the Fraunhofer Institutes´ main field of business. Our close cooperation with industry partners means we can constantly tailor Fraunhofer research to address the challenges that companies face. The infrastructure and organization of the Fraunhofer Institutes are set up for this purpose. The employees at Fraunhofer see it as their fundamental duty to ensure their work always focuses on practical applications. Thanks to their broad customer base, Fraunhofer researchers also have plenty of experience in how customers think and work and have been able to gain insight into different corporate cultures. Companies take care to structure their innovation as effectively as possible. The Fraunhofer Institutes offer customized solutions based on contract research as a cost-effective option: As a partner for concrete projects, the Fraunhofer Institutes work professionally and on schedule. The costs are low and well calculable, compared to the available research capacity within small and medium-sized companies.

Customized Research Cooperations

Customers tend to have a fairly concrete idea of the challenge they are facing and the deadlines they must meet. Often, companies directly approach us or contacts evolve through meetings at events and trade fairs. Once contact has been made, the company is invited to an initial consultation which is both free and without obligation. The goal of this initial discussion is to establish what the objectives would be for a potential cooperative venture and how the budget and schedule might look. This is followed by contract negotiations, the signing of an agreement, and commencement of the research and development work. But what really interests our customers is the fact that Fraunhofer ISE participates in cooperation projects that receive funding from the German state or the EU. An initial consultation can help customers sound out the concrete opportunities to work together on these types of projects.

Fraunhofer ISE caters to the specific needs of each particular client, whether the company wants to bring a new product onto the market, improve a procedure or have a new process tested. Whether your project is to last several years or is of a small specific nature, you will receive the same professional level of research and development services. Our clients include companies from a wide variety of fields ranging in size from small and medium-sized companies up to large global companies.

Proven Framework

Data and information from our customers who use our services are always treated in the strictest confidentiality. We use separate facilities and closed-off laboratory areas wherever necessary to ensure confidentiality. In some cases, competitors from the same industry deliberately choose to work with Fraunhofer in order to create an independent, pre-competitive environment that allows synergies to be exploited.


2


3

Customers that embark on a cooperation project with Fraunhofer receive the rights to the products, prototypes and other material objects that are developed on their behalf. Customers also receive the rights they need to use the inventions, intellectual property rights and know-how generated by Fraunhofer ISE.

Exclusive, application-specific rights of use give the customer optimum protection against competition. Some challenges are so complex that they require multiple partners to develop a solution. Clients in this situation have access to the full range of Fraunhofer Institutes. It is possible to incorporate external partners and additional companies. Fraunhofer researchers have experience in carrying out large projects efficiently and fairly and know what financial support from the government is available. The Fraunhofer-Gesellschaft has representatives worldwide. Our employees have international experience, hold competence in different cultures and languages and first-hand experience with markets worldwide. Thus, companies with international operations can also be served abroad.

Strategic Partnerships and Innovation Clusters

Fraunhofer ISE carries out pre-competitive research to advance promising technological concepts. These self-research projects at Fraunhofer are independent of concrete projects at first. The Institute searches for strategic partners or licensees with whom they can further develop promising technologies and look for companies to bring them to production. Several developments are transferred to the market in spin-off companies set up for this purpose. The Fraunhofer-Gesellschaft initiated the Innovation Clusters and Centers of Excellence to pool the strengths of a region and activate them to solve demanding and cross-sectoral tasks. In addition to industry and universities, the networks include local non-university research institutes that can make important contributions in relevant thematic areas. One example is the Sustainability Center in Freiburg.

Ensuring Customer Satisfaction

Because we cater to the particular research and development needs of our clients, client satisfaction and quality assurance have the highest priority. The positive results from our annual survey on customer satisfaction each year serve as a motivation for us, not least due to the high number of repeat orders and the long-term trustful cooperations with our customers established over the years.

1 *In different projects Fraunhofer ISE carries out research with different industry partners on PV module materials and designs to analyze their effect on the efficiency.*

2 *Within the framework of the group research project TABSOLAR financed by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE developed novel fluid-guiding components based on ultra high performance concrete (UHPC).*
© G.tecz Engineering GmbH

3 *Fraunhofer ISE serves as scientific consultant during the commissioning and operation of the City of Freiburg's new administrative building. One of the project goals is to implement and further develop tools for integrated planning and performance monitoring through all phases, from the planning and commissioning through to the construction, operation and continuous energy monitoring.*

NEW STRUCTURES AND AREAS OF EMPHASIS

Question: **Prof. Henning, Dr Bett, This year's annual report is also a review of your first year as dual directors. Let us first consider the organizational changes that the Institute underwent this year. What are the main structural changes that were made and what were the motives for these changes?**

Henning: The biggest and most visible change is that we have organized the key research areas of the Institute into two large divisions: "Photovoltaics" and "Energy Technologies and Systems". Thematically this is also reflected in the new dual-director structure.

Bett: With two directors, the wide range of research themes of Fraunhofer ISE can be better represented at the leadership level. Prof. Henning is responsible for the system-related topics and I for photovoltaics.

Henning: One motive for the new organization was to better define the internal interfaces and avoid any thematic overlaps. In the course of the years marked by large growth, overlaps occurred in the profiles of different groups and departments. In 2016, we already began to restructure the Division of Energy Technologies and Systems. This year, we added a leadership level over the newly sorted departments and groups. As directors, our goal is to promote a culture of cooperation – an important prerequisite for cross-disciplinary, system-oriented projects in order to reap the full benefit of the extremely broad range of expertise of the Institute.

Question: **Dr Bett, at Fraunhofer ISE about half of all the activities are in photovoltaics. Does this strategic focus reflect the booming global market? In Germany and Europe, industry production hardly exists anymore.**

Bett: Photovoltaics remains a very important focus of Fraunhofer ISE, since it is a key technology for a sustainable energy supply. One big advantage of Fraunhofer ISE is that our research and development activities cover the entire value chain of photovoltaics, from the material to the system integration. The market is growing worldwide: This year, the market volume is expected to be ca. 100 gigawatts, i. e. again an increase of 25 percent. Therefore, we find ourselves working more and more with international customers. In fact, PV cell and module manufacturing in Germany has run into trouble. There are, however, many leading German companies in the fields of materials and production technology with whom we cooperate. There is no doubt that the future will bring new technological developments in photovoltaics. This year we began construction of our new facility "Center for High Efficiency Solar Cells" in order to put ourselves in position to further increase the solar cell efficiency beyond the theoretical boundary of pure silicon material itself.

Question: **Can you be more specific? What developments are possible in the new facility?**

Bett: In the future, we will be seeing multi-junction solar cells on silicon basis on the market. To make this happen, the fundamental developments must be made now. No institute is more suitable for this than Fraunhofer ISE. We have many years of leading expertise in silicon solar cells and at the same time are leading in the field of multi-junction solar cell technology. Also, multi-junction solar cells from silicon and Perovskite play a role. Besides this, we still retain our focus of transferring our newest world record solar cell efficiencies into industrial products. Our PV-TEC facility serves as our power horse here. After the unfortunate fire last year, we are working fast to rebuild the facility in order to again be able to fully serve our customers from industry. We have come far in reducing the cost of photovoltaic electricity. A new aspect of the future will be ecological considerations in the production processes, also recycling.

Henning: We must be aware of just how much renewable electricity we are going to need to achieve a sustainable energy supply. For this, photovoltaics is the only renewable energy that can be integrated in buildings near to where it is

consumed. This is a chance but also a challenge. Photovoltaics will become part of the urban infrastructure. Also here, Fraunhofer ISE with its combined expertise in buildings and photovoltaics is a perfect partner: from the materials and the module development up to the structural and system integration in buildings and quarters.

Question: **Prof. Henning, the simulation model "REMod" was developed at Fraunhofer ISE. It provided the basis for the results of the study on sector coupling from the National Academy of Scientists under acatech's leadership. You are one of the main authors of this study. What actually is sector coupling?**

Henning: Today, we speak a lot about the "second phase" of the energy transformation. On the one hand, we mean the rise of sector coupling, in which renewable energy is used in sectors outside the electricity sector that are presently dominated by fossil fuels. For example, natural gas and heating oil still dominate the heating supply in buildings. A similar situation exists for process heat in the industry, and fossil fuels also serve as the basis in the transport sector. In the coming years, there will be a greater electrification of these sectors – either by directly using renewable electricity or by using synthetic energy carriers, such as hydrogen, which are generated using renewable energy. On the other hand, a related and also important aspect in the second phase is a much greater system integration of renewables.

Question: **How can Fraunhofer ISE contribute to the second phase of the energy transformation? What are the key strategic areas of the Institute within this context?**

Henning: There are many working areas at Fraunhofer ISE that can provide important contributions here. One example is building energy technology. Besides increasing the building energy efficiency, it will also be important to increase the use of renewables in the building energy supply. To this end, we have greatly expanded our research in the field of heat pumps over the past five years. Storage technologies are also becoming more and more important. Therefore, we are putting more concentration on batteries and are now including battery cell production in our repertoire. Power electronics plays a large role in system integration and is another key technology under expansion at Fraunhofer ISE. In addition, we are convinced that the role of hydrogen will be key in the coming years and over the next decades for the conversion of renewable electricity into chemical energy carriers. These shall replace fossil fuels little by little, e. g. in heavy load, ship and aviation transport. Not least, solar thermal power plants remain in our focus. This technology is experiencing a large reduction in costs and make a demand-driven energy supply possible when coupled with an integrated thermal storage.

Question: **Prof. Henning, you are also Speaker of the Fraunhofer Energy Alliance. How do you see the positioning of energy topics within the Fraunhofer-Gesellschaft?**

Henning: The institutes of the Fraunhofer-Gesellschaft command a large spectrum of research topics, especially in the fields of energy efficiency and renewable energy. They hold the leading position in many fields in Germany and also internationally. In my view, the competence available at the individual institutes can be brought together even more. This is an important goal that I have adopted in my role as Speaker of the Fraunhofer Energy Alliance and would like to carry out in close coordination and cooperation with executive board and the headquarters of the Fraunhofer-Gesellschaft.

1 *The Institute Directors Prof. Hans-Martin Henning (left) and Dr Andreas Bett (right).*

BATTERY RESEARCH – THE FUTURE DIRECTION AND PROJECT EXAMPLES

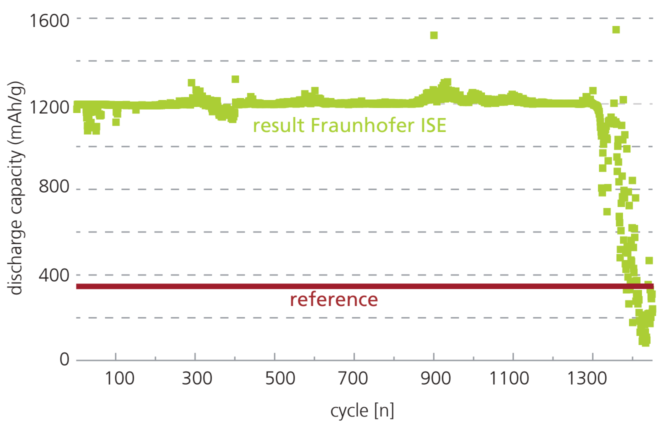
Battery Technologies of Major Importance

Rechargable batteries are a key technology for the 21st century. Electrical storage is increasingly gaining importance in modern society in nearly all areas of life for stationary, yet more so, for mobile applications. Therefore, it is of utmost importance to control and ensure the availability of battery and battery component production at all steps along the value chain.

Fraunhofer ISE has been carrying out intensive research on battery systems for decades. The focus of our activities along the value chain ranges from cell characterization and module design through to charging electronics and battery management up to integration and optimizing the operation of the entire system. Over the past years we have greatly enlarged our facilities for energy performance testing, covering all aspects of efficiency and effectivity of battery storage, aging investigations and post mortem analyses. We offer battery manufacturers and users consulting, development and testing services based on conventional standards and safety requirements as well as on customer-specific test protocols. We also plan to expand our certification services that rely on established test procedures and guidelines to include entire systems. Here, we can take advantage of our in-house expertise in photovoltaic power plants as well as our wide range of activities in power electronics, a very important aspect for photovoltaics or wind power in combination with battery storage and grid integration.

In a comprehensive strategic planning process, we decided to expand our R&D activities to include battery cells. For the development of novel battery cells as well as the technology transfer from the laboratory to industrial processes, Fraunhofer ISE can build on its extensive long-term expertise in photovoltaics and also in optically functional layers. These include competence in materials and technologies as well as a deep understanding of the relevant manufacturing processes including detailed cost analyses.

A main focus of our newly launched work follows out our extensive expertise in silicon material, which we have acquired from our successful research on silicon solar cells extending over decades. Thus, we were able to demonstrate a lithium ion half-cell with silicon anode that repeatedly reached a discharging capacity three times higher than a standard electrode for over more than 1200 cycles (see graph.) A second focus lies in transferring the new cell concepts to industrial production. This is also a topic where we can greatly profit from our related expertise acquired in the field of photovoltaics.



Graph: Discharge capacity of a silicon anode developed at Fraunhofer ISE with 1200 mAh/g capacity during cycling in comparison to a reference anode based on graphite (about 350 mAh/g).

Project Examples from Battery Research

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Silicon-based Anodes for Powerful Lithium Ion Batteries

Silicon is one of the most promising materials for next-generation anodes in powerful, compact lithium ion battery cells. Silicon can store appreciably more lithium ions than graphite with the anode yielding a theoretical specific capacity of almost one magnitude higher. However, battery cells with silicon-based anodes have shown only a very low cycle stability up to now. Based on our specific knowledge of silicon, we could already achieve promising results in our developments of silcon-based anodes. In a novel process, we covered silicon particles with a thin carbon layer that promises a higher cell stability. In the first experiments, we could show that the anodes based on this novel silicon material evidenced both high cycle stability and also the ability to store a very large amount of lithium.

Security Requirements for Batteries

Compared to conventional battery technologies like lead acid and NiMH, lithium ion batteries have a much higher storage density. They also have, however, a higher risk potential; for example, if they are damaged or if the authorized operating conditions are not adhered to. Through past experience with grid-connected and autonomous PV power plants, Fraunhofer ISE has collected many years of expertise on the protection against accidental contact and short-circuit. Now this acquired competence can be transferred to the operation of battery systems. In order to rule out risks from lithium ion batteries, we are developing improved battery management systems in various projects, some of which are financed by the German Federal Ministry for Economic Affairs and Energy (BMWi). These systems shall help to avoid critical operating situations and at the same time increase the battery lifetime.

Batteries for Electric Mobility

The biggest technological challenge facing electric mobility is the battery. Batteries for electric vehicles must be powerful, safe and reliable and guarantee a long driving range. Large temperature fluctuations and high loads during fast charging put large demands on the thermal management. At Fraunhofer ISE we have developed a systematic process in which we, together with our customers, can choose the optimum lithium cell for the given application. The process consists of performing electric and thermal characterizations of cells of any size as well as determining the calendrical and cyclical aging by recording changes in cell parameters over the battery lifetime. In the EU sponsored project MARS-EV, we showed, using stochastic filter systems, that the aging and state of charge of the vehicle battery can be precisely determined in situ at any point in time. Based on this work, both models coupling thermal and electric behavior as well as operating strategies for the energy management were developed. In the EU sponsored project JOSPEL, we were able to demonstrate that with an optimized battery operating strategy an energy saving of over 12 % and a lifetime extension of 15 % could be reached at the same time.

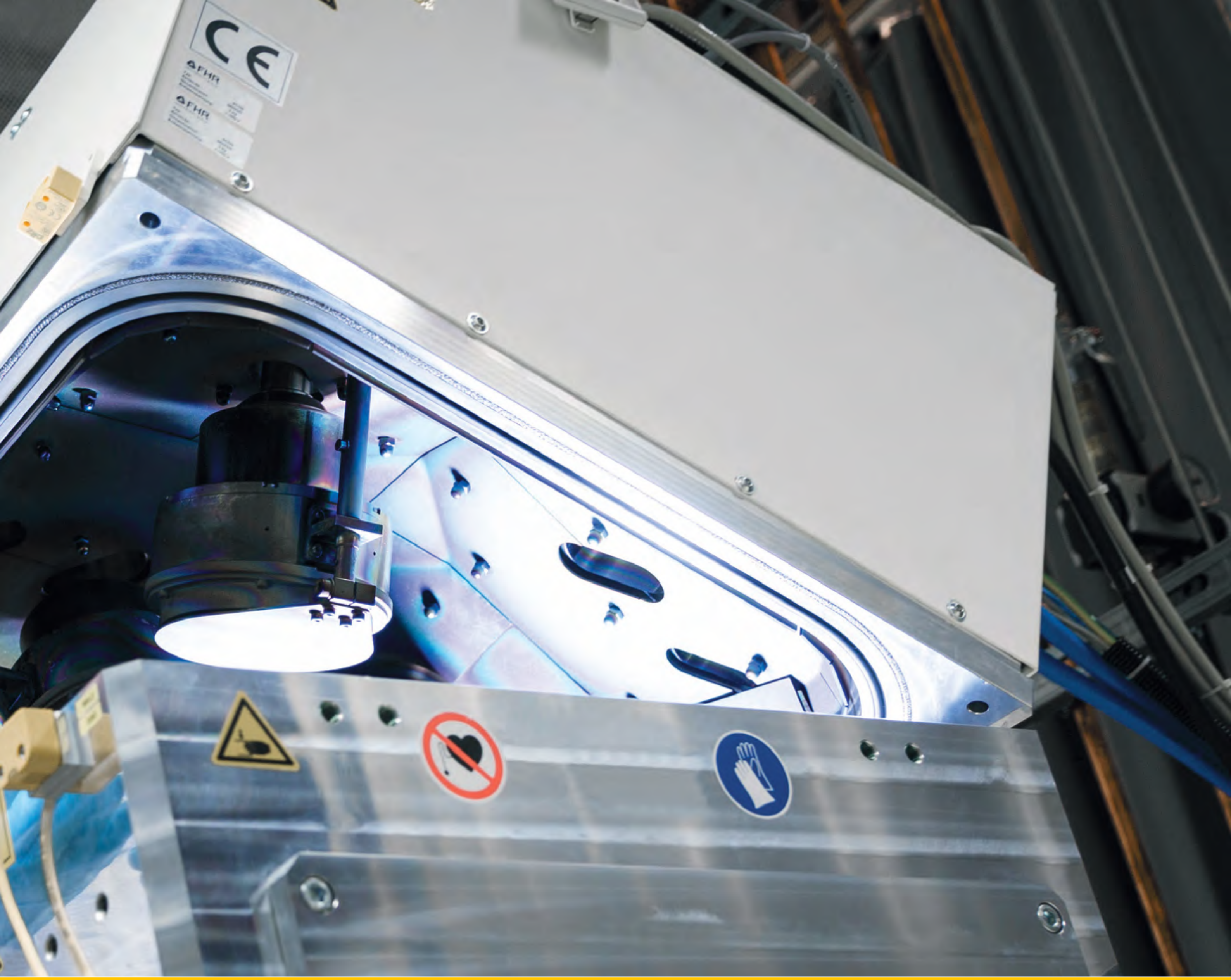
1 *Investigation of lithium ion batteries carried out in a glove box.*

PHOTOVOLTAICS

At the Climate Change Conference in Paris in 2015, the global community agreed to limit the temperature increase of our atmosphere to a maximum of 1.5 °C and thus to implement a global energy transformation. Photovoltaics is a central pillar for an economically and ecologically achievable energy supply. Over the past ten years, module prices have fallen from approximately 2.70 €/W to approximately 0.40 €/W. This means that competitive values for the levellized cost of energy of less than 5 € cent/kWh are possible today in Germany. The global photovoltaic market is also expanding accordingly with high growth rates. In 2016, the increase was more than 30 %, and by the end of 2016, the cumulative globally installed photovoltaic power amounted to one third of a terawatt. Photovoltaics is booming and will continue to grow rapidly!

Research and development have made essential contributions to this success story. Also, this year, Fraunhofer ISE can present excellent R&D results. We are particularly proud of the improved efficiency values which we achieved for monocrystalline and multicrystalline silicon solar cells. The TOPCon contact passivation technology (Tunnel Oxide Passivated Contact) developed at Fraunhofer ISE played a special role in these achievements. Good silicon material provides the foundation for high solar cell efficiency values. Thus, we have developed special high-performance silicon, which was used as the starting point for our multicrystalline solar cell with a record efficiency value of 22.3 %. Great progress in the development of monocrystalline

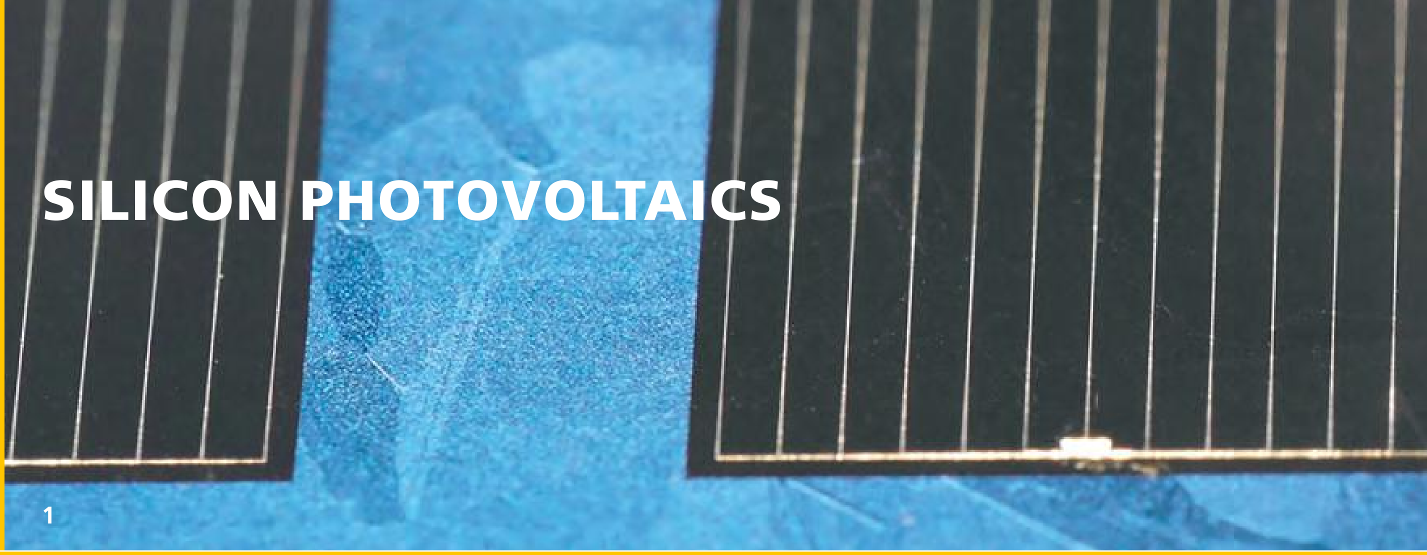
i Sputtering equipment to deposit anti-reflective coatings and metal contacts.



material was also made at the Center for Silicon Photovoltaics (CSP) located in Halle / Saale. Our R&D work on wafering is carried out in the Technology Center for Semiconductor Materials (THM) in Freiberg. Preparatory research for industrial implementation is carried out by Fraunhofer ISE in our Photovoltaic Technology Evaluation Center PV-TEC. Recently, we established a basic process there for monocrystalline Si PERC solar cells with a stable average efficiency value of 21 %. At the end of February, 2017, a fire destroyed the main building of PV-TEC. Fortunately, most of the planned R&D work could be continued in other laboratories. Reconstruction of PV-TEC is already well underway and we are confident that it will become fully operational in spring 2018.

In addition, Fraunhofer ISE has further developed successful procedures for accurate characterization and yield analysis, particularly of bifacial cells and modules. Our accredited calibration laboratory, CalLab PV Modules, was able to achieve an internationally leading measurement uncertainty of only 1.3 %. Top efficiency values of up to 46.1 % have been achieved with multi-junction solar cells based on III-V semiconductors in combination with optical concentrator technology. We were able to use our long-term experience with the production of multi-junction solar cells to produce a monolithic multi-junction solar cell of GaInP/GaAs/Si with an efficiency value of 33.3 %. This promising technology demonstrates how the Auger limit for single-junction silicon solar cells of 29.4 % can be overcome in future developments. Our work on organic and perovskite solar cells also opens up interesting perspectives and applications.

With our portfolio, we are well equipped for the future and are contributing to developing yet more efficient photovoltaics – with respect to the energy yield, but also with regard to manufacturing procedures and use of materials. Our ambitious goal is to achieve a processing chain along the complete value chain which is simultaneously cost-effective and sustainable.



SILICON PHOTOVOLTAICS

More than 90 % of all solar cells that are produced throughout the world are made of crystalline silicon. The keys to this dominant market position are a robust and cost-effective manufacturing process on the one hand and the high efficiency and great reliability of silicon-based PV modules on the other. In particular, the efficiency value plays a decisive role for further reducing the levellized cost of energy and is thus the focus of research activities.

Fraunhofer ISE supports the research and development by manufacturers of materials, modules and production equipment with its internationally unique R&D infrastructure in laboratories and prototype production facilities covering more than 3000 m² floor area. The scientific and technological competence of our more than 300 scientists, engineers and technicians spans silicon material, through solar cells and modules, to complete systems. As a result, our cooperation partners have access not only to individual technologies but can work together with us along the complete value chain.

The technological readiness level encompasses the complete bandwidth from laboratory research to industrially relevant development. With new technologies and international records in efficiency values from our research laboratories, we repeatedly establish new scientific trends in photovoltaics and thus provide important stimuli for new developments. In our Technology Evaluation Centers with their industrially relevant infrastructure, PV-TEC and SiM-TEC, we can evaluate more mature concepts under realistic conditions and develop innovative manufacturing processes that are ready for transfer to industry. In addition to modern technology, thorough characterization of the underlying processes and careful quality assurance throughout the entire value chain is extremely valuable for our clients and cooperation partners.

328
Total staff

67
Journal articles and contributions to books

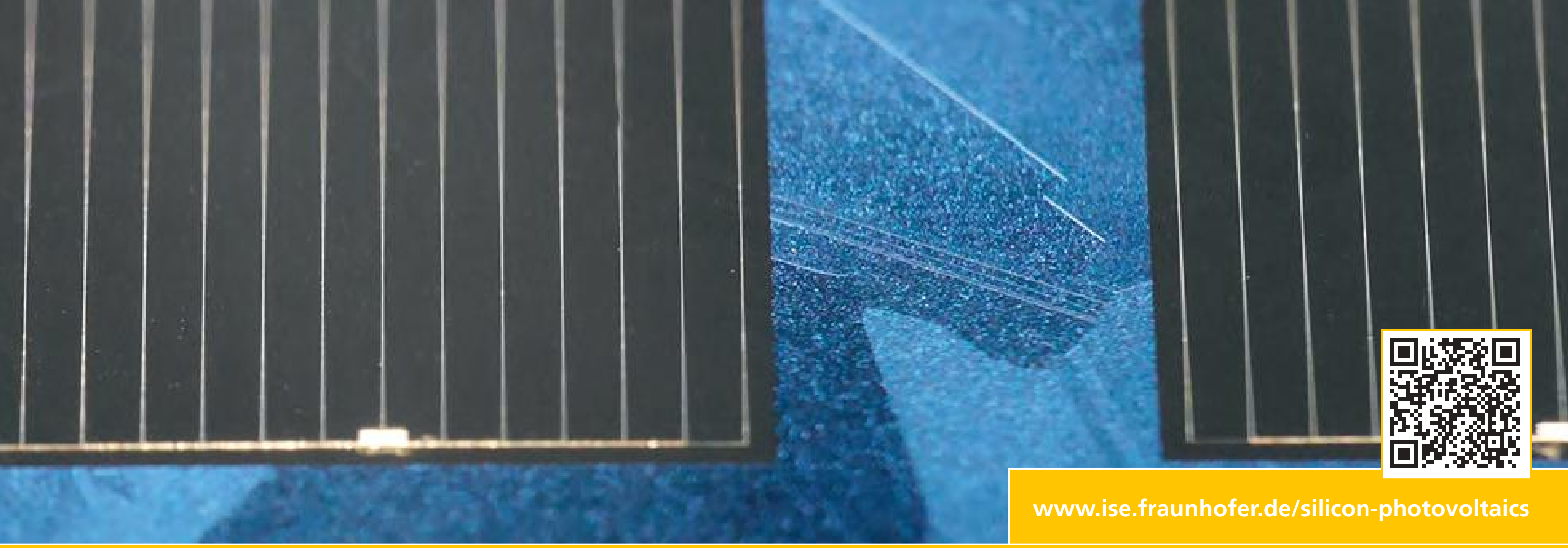
51
Lectures and conference papers

14
Newly granted patents

1 *The multicrystalline world-record solar cell of n-type high-performance silicon material has an area of 2 cm x 2 cm. The cell has a very good anti-reflective coating, such that it appears almost black and the grain boundaries of the silicon material are hardly visible.*

Milestones in 2017

- 22.3 % world record efficiency value for solar cells of multicrystalline silicon.
- Best silicon solar cell with bifacial contacts and an efficiency value of 25.8 %.
- Foundation stone laid for the Center for High Efficiency Solar Cells, which will offer the most recent laboratory infrastructure.
- 21.5 % efficiency value achieved for industrial PERC solar cells.
- First bifacial shingle solar cells with an efficiency value of 20 %.



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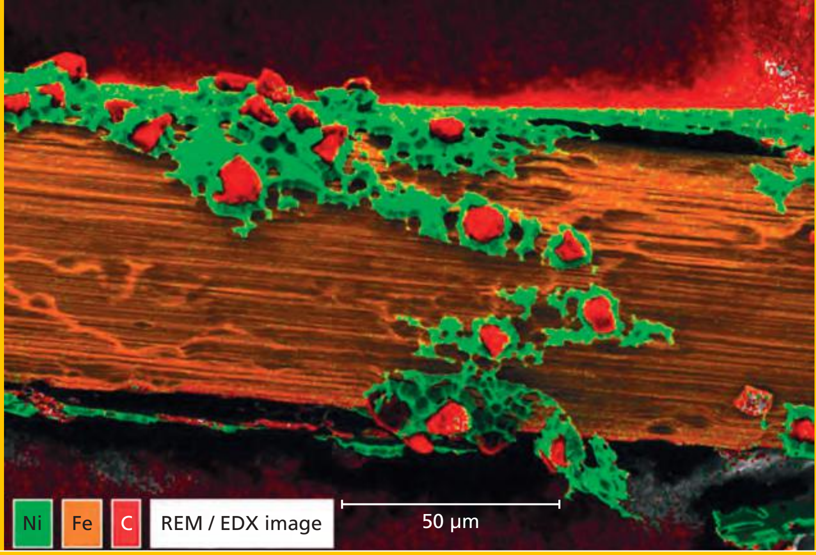
Selected Projects in 2017

- CUT-A – Cutting-edge characterization and technology for the German PV industry, Project Part A
- Rock-Star – Evaluation and development of rotary printing procedures for the production of Si solar cells
- Nano-Tandem – Nanowire-based tandem solar cells
- SiTaSol – Application relevant validation of c-Si based tandem solar cell processes with 30 % efficiency target

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



High-Performance Multicrystalline Silicon Wafers Sawn with Diamond Wires

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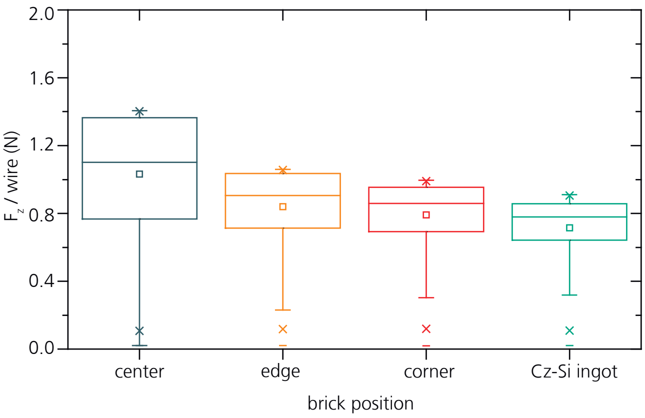
High-performance multicrystalline silicon (HP mc-Si) is distinguished by a lower number of dislocations and thus higher material quality than conventional mc-Si. It can therefore be assumed that HP mc-Si will completely replace standard material in future. Its high efficiency potential was proven with a world record efficiency value of 22.3 % for n-doped material.

To reduce the costs in producing mc-Si solar cells still further, it is necessary to transfer the wire-sawing step from the established slurry procedure to diamond-wire sawing technology. By using water as the cooling lubricant and higher feeding rates, this process is more cost-efficient. Whereas this transfer has already been largely completed for monocrystalline silicon, more development is needed for mc-Si. This applies to both the further development of the sawing processes and also the diamond wires and the subsequent texturing of the wafers.

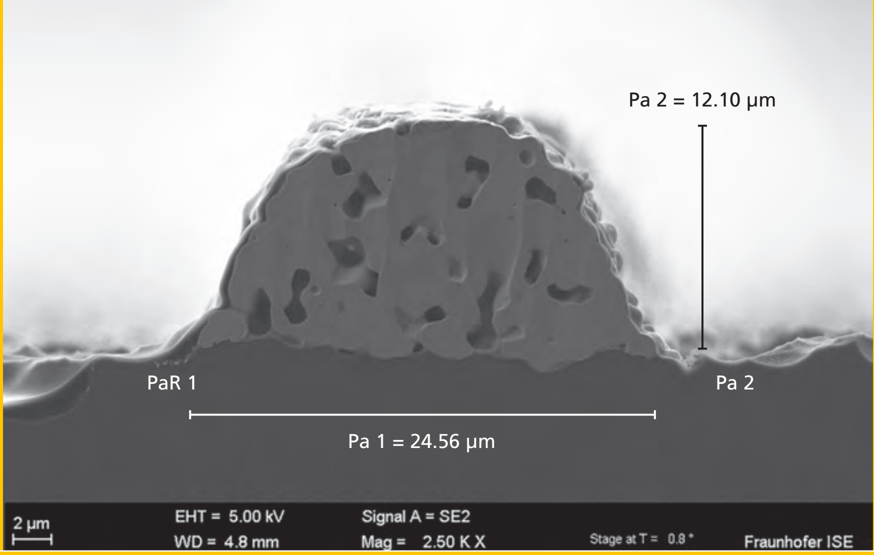


Graph: Force in the feeding direction F_z for HP mc-Si bricks from different positions in an ingot; the larger F_z is, the lower is the cutting efficiency.

1 *REM / EDX image of a diamond wire while the diamonds and nickel coating are being etched away to enable analysis of the diamonds; representation of an intermediate step.*

With specifically selected diamond-wire sawing processes, Fraunhofer THM has contributed to a fundamental understanding of the material properties which affect the cutting efficiency. For instance, a significant difference in the cutting efficiency of HP mc-Si bricks was found as a function of their position within the ingot. Bricks from the edge and corner zones can be cut significantly more easily than bricks from the center of the ingot, as was demonstrated by the force F_z in the feeding direction during the sawing process (see graph). The lower the value of F_z, the better is the cutting efficiency and the lower is the wire wear. For the edge and corner bricks, F_z is only 10–20 % larger than for the Cz-Si reference ingot.

We identified the size of silicon nitride and silicon carbide precipitates to be the main cause of the lower cutting efficiency. In the bricks from the ingot center, significantly larger precipitates are present than in the edge and corner bricks, but the distribution also varies for different crystallization processes. By pre-sorting the bricks and applying appropriate feeding rates, the industrial diamond-wire sawing process and the wire consumption can be optimized. The characterization of the wires includes determination of the diamond grain density on the wire, exact measurements of the grain size distribution before and after the process, and detailed analysis of the grain form. We have developed a process which enables the diamonds to be completely separated from the wire and used for a process-related analysis.



Solar Cell Production Technology – Dispensing Metal Contacts

Dr Maximilian Pospischil | Phone +49 761 4588-5268 | sipv.contact@ise.fraunhofer.de

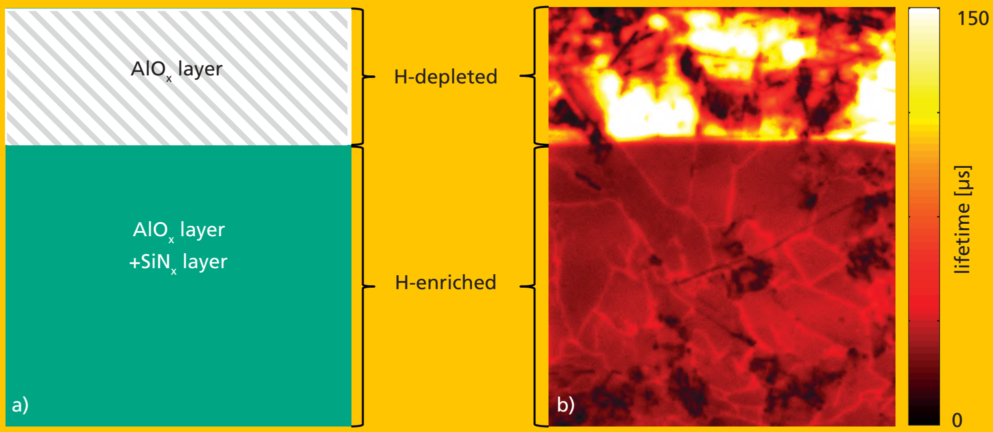
A central production step in manufacturing silicon solar cells is depositing metal contacts onto the front and back surfaces to allow the generated electricity to be extracted. Dispensing is one possible alternative to the classic screen-printing process, which has been used for decades for this purpose. In the dispensing process, which is already used frequently in adhesive and soldering technology, the medium to be dispensed is squeezed through a thin nozzle and deposited onto the required object from a certain distance. In this way, both the resulting geometrical form of the fingers can be improved and the mechanical load on the wafer during the metallization step can be significantly reduced.

Within the "Gecko" project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), a parallel dispensing process was established at Fraunhofer ISE in cooperation with the industrial partners, Heraeus, ASYS and Merck. The core components here are specially developed dispensing printing heads, which can subsequently be installed in industrially relevant automation platforms. In cooperation with ASYS, the previously developed prototypes with ten nozzles in parallel were scaled up to a version with a 16 cm processing width, whereby the deviation in the mass flow rate for the 50 nozzles arranged in parallel amounts only to approximately 1 %. Using this printing head, solar cells can be printed without direct contact at printing speeds of up to 1 m/s. This offers appreciable potential for increasing throughput compared to conventional flat-bed screen-printing facilities.

The extreme homogeneity of the contact fingers means that the amount of silver paste applied can be reduced by approximately 15 wt-% compared to screen-printed structures, while still using the same, commercially available screen-printing paste. At the same time, because the contact fingers are only 27 µm wide, the efficiency value of the resulting solar cells is increased by approximately 1 $\%_{rel}$ compared to screen-printed references. A similar increase was determined by comparing two screen-printing pastes from different manufacturers on industrial-type solar cells. An efficiency value of 21.4 % was achieved there. In a further experiment, we achieved a reduction in the silver paste consumption (wet deposition) by 60 % to only 48 mg per wafer while the efficiency value (of 21.2 % in this case) remained unchanged. The resulting contact fingers were only 25 µm wide and 12 µm high.

Since June 2017, we have worked intensively on the commercialization of the technology within the "EXIST-Forschungstransfer" initiative funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The project goal is to develop an industrially applicable dispensing printing head, whereby the greatest technological challenge is posed by the requirement of stable, intermittent operation (deliberate interruption of the contacts at the cell edges) by the dispensing printing heads. In the next phase, extensive tests will be conducted together with industrial partners, with the goal of increasing the technological readiness level to the point that it can thereafter be introduced directly into industrial series production.

1 *SEM image of a dispensed contact finger, which enables the silver paste consumption to be reduced to less than 50 mg per solar cell.*



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Defects due to Light-Induced Degradation in Multicrystalline Silicon

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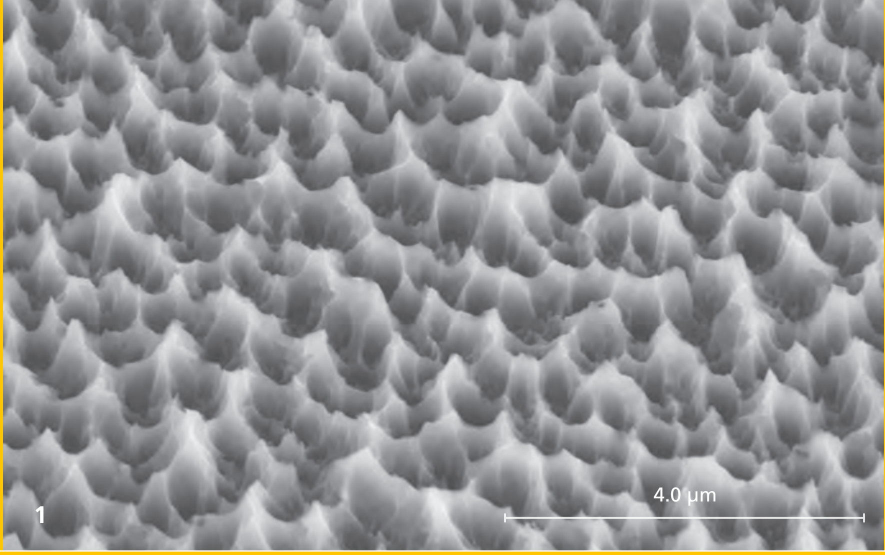
In PERC solar cells, light-induced degradation of the material occurs, which has not yet been explained in detail and which impedes the industrial implementation of the PERC concept on multicrystalline silicon. In accordance with the operating conditions of solar modules, it is called LeTID (light and elevated temperature-induced degradation). Fraunhofer ISE is involved within the "SolarLIFE" research cluster funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) in investigating this effect, together with other German research institutes and industrial partners.

We have succeeded in taking a large step toward identifying the defect. Investigations on extremely pure (float-zone) silicon revealed that this material also shows light-induced degradation at elevated temperatures when it is subjected to a typical PERC processing sequence. In a targeted investigation, we determined that the occurrence of the degradation depends on whether a silicon nitride layer is present on the wafer during the firing step. This behavior is also observed in multicrystalline silicon, as is shown as an example in Fig. 1: the extent of degradation differs considerably even over a single sample, if the silicon nitride layer is not deposited over the complete surface. In addition, we observed that the degree of degradation increased with higher firing temperatures for both extremely pure and multicrystalline silicon. The degradation and the subsequent relaxation occurred over a much shorter timescale for the extremely pure samples.

These observations agree well with the insights on reaction kinetics which we gained from experiments with multicrystalline solar cells. The specific pre-treatment conditions, under which LeTID occurs not only in multicrystalline but also in extremely pure silicon, indicate that atomic hydrogen is involved in the defect. This is introduced from the silicon nitride into the bulk material of the wafer during the firing step. Within the wafer, it is normally advantageous, because many defects are deactivated by adsorbed hydrogen. We assume that the defect associated with LeTID is one that becomes harmful only after hydrogen has been added. Further investigations to identify the other species involved are continuing.

1 *Luminescence-based lifetime measurement on a multicrystalline wafer with different passivation layers: a) sample configuration, b) degraded state.*



Novel Passivating Contacts

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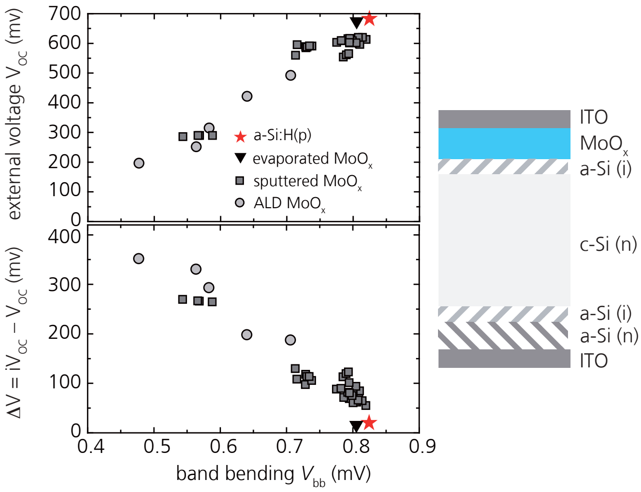
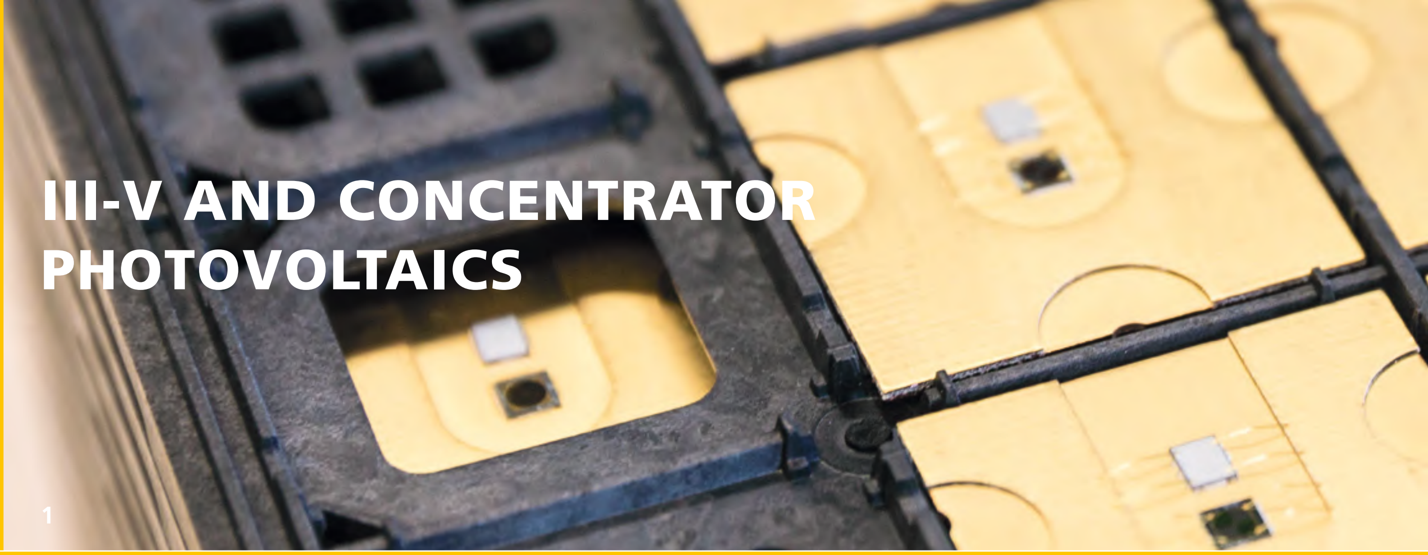
To further reduce the levellized cost of electricity from modern silicon solar cells, the recombination of light-generated charge carriers must be reduced, particularly at the contacts. Contacts with excellent passivation properties can be implemented, e. g. with the TOPCon technology that was developed at Fraunhofer ISE. In this process, we initially allow a very thin oxide layer to grow on the silicon wafer and then deposit onto it a heavily doped silicon layer with a crystalline structure that can be deliberately influenced by the subsequent high-temperature step. With this TOPCon structure as the back-surface contact of a monocrystalline n-type silicon solar cell, we achieved efficiency values of 25.8 % on small areas and 24.5 % on large solar cells. TOPCon technology is also very well suited for multicrystalline silicon, so that we were able to improve the present world record efficiency value to 22.3 %. At Fraunhofer ISE the complete solar cell technology was developed and the crystalline growth of the applied high-performance multicrystalline silicon also took place there. This demonstrates the great potential of the complete value chain, from materials up to systems, which is represented at the Institute. At present, we are transferring the TOPCon technology from the laboratory environment of our clean room to PV-TEC, our industrial pilot line for solar cells with passivating contacts.

Due to the heavily doped Si layer that is used, however, parasitic absorption losses can occur when TOPCon technology is applied to the front surface of the solar cell. Thus, we are very interested in passivating contacts based on metal oxides for this application. To this purpose, we combine a very thin, undoped amorphous Si layer (a-Si (i)) with a metal oxide layer such as molybdenum oxide (MoO_x). Due to the high work function of MoO_x, band bending occurs in the silicon, which strongly increases the hole conductivity and thus results in the desired charge-carrier selectivity. We have investigated this fundamental effect comprehensively and deposited MoO_x with different compositions, applying different techniques (see graph). Only when the resulting band bending is large enough the internal potential (iV_{oc}) of the solar cell, which is created by illumination, is fully present at the external contacts (V_{oc}). By applying these and other investigations, we have deliberately optimized the new contact system and used it as the front contact grid for n-type solar cells. The achieved efficiency value of 22.6 % demonstrates the great potential of this technology.



Graphs: Influence of band bending on the external potential (V_{oc}) of an MoO_x-based contact system (above). If the band bending or the electron affinity of the MoO_x layer is too weak, large losses (ΔV) appear between the internal (iV_{oc}) and external voltage (V_{oc}) of the cell (below). By contrast, if the work function is high enough (app. 0.8 eV), the very good properties of the reference system of amorphous silicon (red star) can be achieved.

1 *Surface texture of the record multicrystalline solar cell.*



III-V AND CONCENTRATOR PHOTOVOLTAICS

1

In this sector, Fraunhofer ISE addresses the demands of space and concentrator photovoltaics. In addition, we work on efficient conversion of light from sources like lasers into electricity. We investigate both solar cells of the next generation with optimized structures and efficiency values and also the adaptation of these components to the specific requirements of our clients. Thus, we develop e. g. ultra-thin and light solar cells, which can be attached to curved surfaces, or concentrator solar cells with areas between 0.1 mm^2 and 1 cm^2. In all cases, we aim for components with low production costs, high reliability and high efficiency.

In concentrating photovoltaics, we cover all aspects from the solar cell to the module and optimize the complete system. To do so, we apply our expertise in optics, mounting and connection technology, as well as theoretical modelling and module design. We thus serve a heterogeneous market of enterprises which develop PV systems with low to very high concentration factors. For the latter, our expertise also extends to system aspects such as application of the generated heat or direct production of solar hydrogen for energy storage. We achieve innovations by systems-relevant conception and set ourselves the goal of providing the best solutions in the world for our clients.

We can draw on excellent infrastructure for our work. Our particular expertise is in the development of semiconductor structures with mismatched crystal lattices, which we implement by metamorphic growth, wafer bonding or growth on engineered substrates. In this way, we can combine GaAs with silicon or InP within a single device.

55
Total staff

20
Journal articles and contributions to books

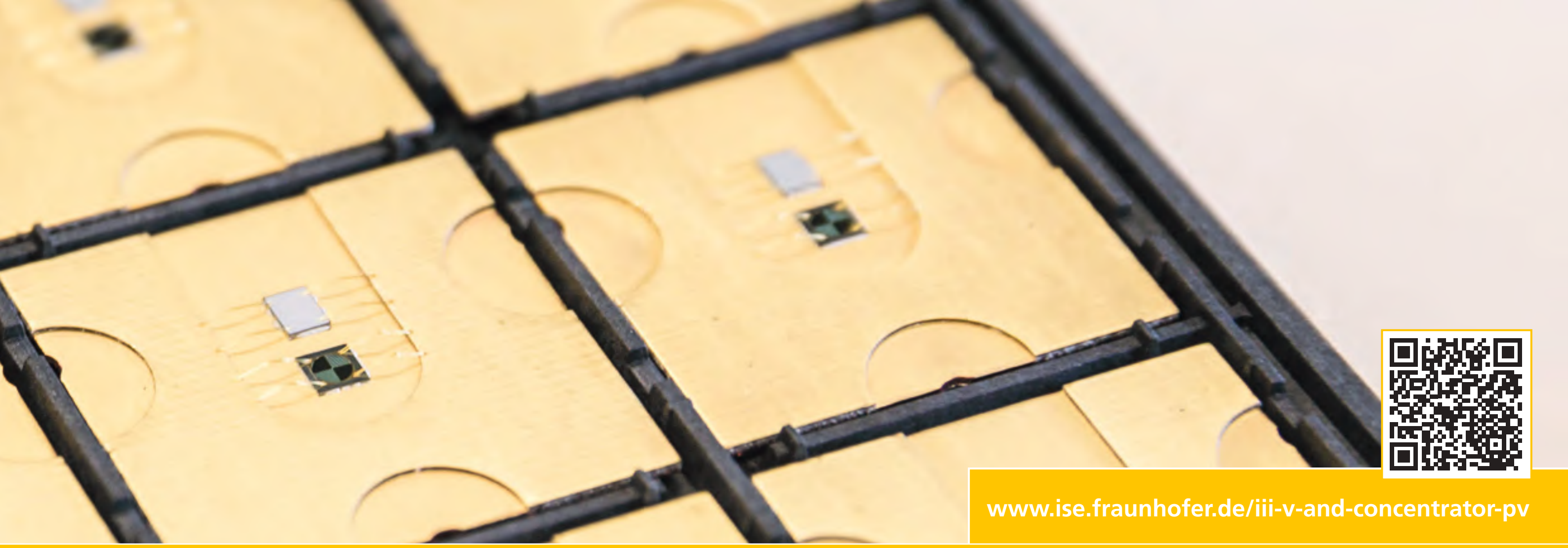
11
Lectures and conference papers

3
Newly granted patents

Milestones in 2017

- Semiautomatic production of FLATCON® concentrator modules with optimized lens and module design established. The production processes were demonstrated successfully with prototypes. Now we are looking for partners for industrial implementation.
- Cost reduction of III-V semiconductor structures by optimizing growth conditions. For the first time, GaAs layers for solar cells were grown at rates of 140 µm/h and low consumption of AsH_3.
- The further development of ultra-thin solar cell technology with back-surface reflectors led to GaAs concentrator solar cells with an efficiency value of 28.8 % under concentrated light and laser power converters with an efficiency value of 67.3 % under illumination with an 860 nm laser.
- Foundation stone laid for the Center for High Efficiency Solar Cells, in which III-V semiconductor components will be further developed with the most modern infrastructure from 2020 onward.

1 *Concentrator solar cells with a bypass diode on cooling blocks before installation in a FLATCON® concentrator module.*



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

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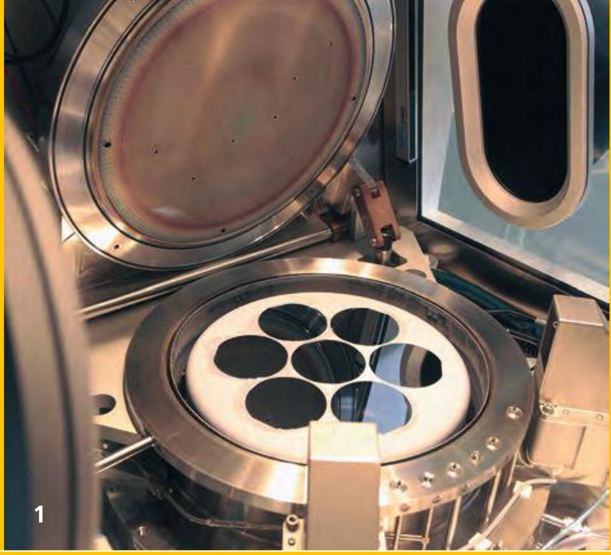
Selected Projects in 2017

- Nano-Tandem – Tandem solar cells based on nano-wires
- SiTaSol – Application relevant validation of c-Si based tandem solar cell processes with 30 % efficiency target
- ALCHEMI – A low cost, high efficiency, optoelectronic HCPV module for 1000 sun operation

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



Cost-Effective Epitaxial Processes for III-V Semiconductors

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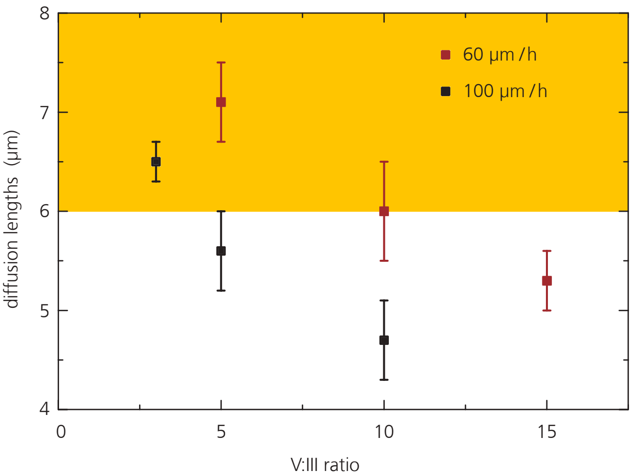
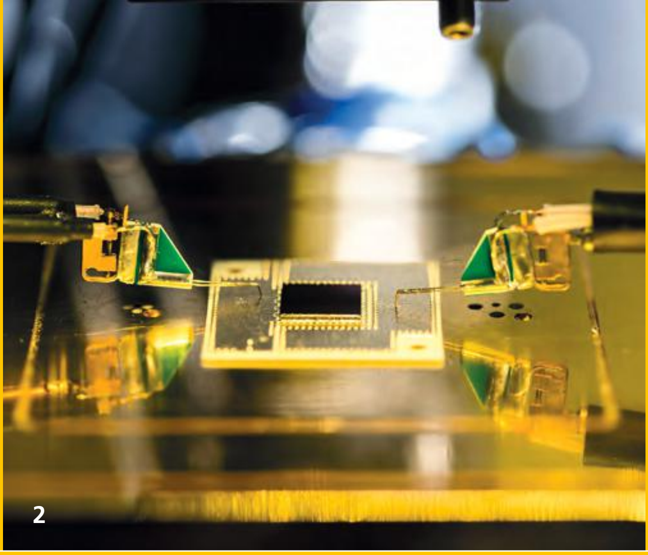
Solar cells of III-V semiconductors, whether as single-junction or multi-junction cells, hold all efficiency records at present. Single-junction GaAs solar cells reach efficiency values up to 28.8 % (1 sun) and four-junction solar cells from Fraunhofer ISE achieve up to 46.1 % (312 suns). Despite the high efficiency, III-V solar cells are not widely used. At present, they are used commercially mainly for space applications, as they offer advantages there due to their greater tolerance to cosmic radiation. The main terrestrial application of III-V solar cells is in concentrator modules, which, however, constitute only a small fraction of the global photovoltaic market. More widespread application of III-V high-efficiency solar cells could be achieved if the price for the raw materials and epitaxial processes were reduced.



Graph: Minority charge carrier diffusion length in p-GaAs as a function of the V / III ratio for deposition rates of 60 µm/h (red) and 100 µm/h (black). Diffusion lengths exceeding 6 µm are sufficient for the carrier separation in GaAs solar cells.

1 *View into the III-V epitaxial reactor at Fraunhofer ISE with a coating area of 700 cm².*

This is exactly the starting point for current research projects at Fraunhofer ISE. In order to reduce the production costs for III-V epitaxy significantly, we are conducting research on increasing the deposition rates by more than an order of magnitude and simultaneously retaining the good optical and electrical properties of the materials. High growth rates allow shorter processing times and thus reduce the need for epitaxial equipment including all the necessary infrastructure. In the "MehrSi" project, funded by the German Federal Ministry of Education and Research (BMBF), we were able to increase the growth rate for GaAs solar cell layers from < 10 µm/h to more than 100 µm/h for the first time. Production equipment with a deposition area of 700 cm² from the Aixtron company was used for this (Fig. 1). The layers feature diffusion lengths exceeding 6 µm and thus high crystalline quality (see graph). With the new process, a 3 µm thick GaAs absorber layer of the solar cell can be deposited in less than two minutes. In the "KoReMo" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), we also address high growth rates and make use of an innovative direct evaporation system from the Sempa company. With this approach, we aim to increase the growth rates significantly, not only for GaAs but also for GaInP layers. Further cost reduction is achieved by direct growth of III-V layers on silicon instead of on germanium or gallium arsenide. In this way, we have already produced GaInP/GaAs/Si solar cells with an efficiency value of 19.7 %. This is currently the highest value for a three-junction cell grown on silicon, but the potential is significantly higher still. In future, the processes and material quality are to be optimized further. Rapid and direct growth of the III-V stacks on silicon then offers the chance to reduce the cost of highest-efficiency III-V solar cells significantly and thus to penetrate new markets. Examples include applications with limited available area such as car roofs, drones and electronic devices; on the long term, highest-efficiency rooftop applications are conceivable.



Highly Efficient Photovoltaic Laser Power Converters

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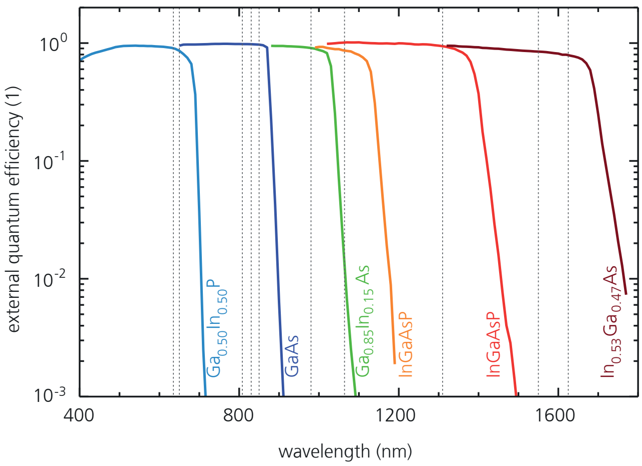
In our work at Fraunhofer ISE on "Power by Light", we investigate highly efficient photovoltaic cells as converters for monochromatic laser light. They are used in optically powered electronic systems, i. e. in systems which draw their energy from laser illumination rather than via a cable. This guarantees galvanic isolation between the base and the receiver and ensures electromagnetic compatibility. In addition, by avoiding conventional copper cables, the risk of electric sparks is avoided and weight advantages can be obtained. Applications of this optical energy transmission are very diverse and range from supplying power to sensors in critical environments (e. g. in aircraft fuel tanks or in high-voltage zones) to wireless power transmission for consumer electronics.

In contrast to solar cells, which are optimized for efficient conversion of the broad band solar spectrum, the main loss mechanisms there – transmission and thermalization losses – can be almost completely avoided in laser power converters. However, to achieve this, the absorber material must be optimally tuned to the laser wavelength. To this purpose, we use our high-throughput MOVPE (Metal-Organic Vapor Phase Epitaxy) reactor to develop absorber layers based on III-V semiconductors of high material quality and for diverse applications. By using III-V compound semiconductors and exact adjustment of the composition, we can finetune the band gap optimally to the photon energy of the laser radiation (see graph).

Based on a GaAs cell with a highly reflective backside mirror to minimize optical losses, we have demonstrated a monochromatic efficiency value of 67.3 % with a 0.054 cm^2 small cell irradiated with a laser beam at 860 nm. With a 1 cm^2 cell based on InGaAsP, we have achieved a monochromatic efficiency value of 48.3 % at 1310 nm.

Furthermore, we work on series-connected cell architectures with elevated output voltage. This is advantageous in certain applications, as additional electronic voltage conversion is no longer needed, avoiding the associated power losses. Here, we are pursuing concepts for lateral interconnection of several segments on semi-insulating substrates (multi-segment cells or MIMs) and also vertical stacking and series-connection via tunnel diodes (multi-junction cells).

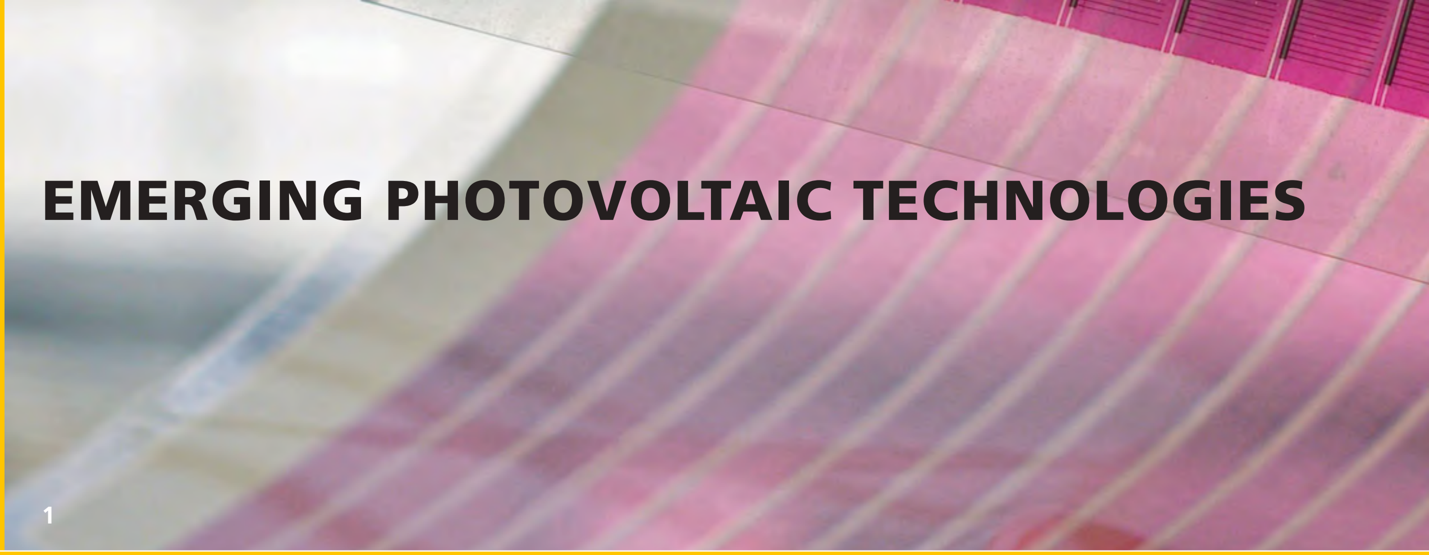


1 *Measurement set-up in Fraunhofer ISE CalLab PV Cells for measurement of current-voltage characteristics of PV cells under monochromatic irradiation.*

2 *Photovoltaic laser power converters with an active area of 10 × 10 mm², mounted on a planar substrate.*

Graph: Measured external quantum efficiency values of different III-V-based photovoltaic cells with appropriate absorption edges for various common laser wavelengths (dotted lines).

EMERGING PHOTOVOLTAIC TECHNOLOGIES



34 Total staff

12 Journal articles and contributions to books

3 Lectures and conference papers

2 Newly granted patents

Emerging Photovoltaic Technologies encompasses organic, dye and perovskite solar cells, photon management and tandem solar cells on crystalline silicon. The aim is to exploit optimization potential in photovoltaics with the help of these novel technologies and to reduce the levellized 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 by advanced photon management. Another approach is provided by alternative processes and materials such as organic, dye and perovskite solar cells, which offer clear potential for cost reduction, making them promising research objects despite their lower efficiency values.

Our work on organic solar cells has the goal of realizing cost-efficient, flexible and durable organic solar modules. We cooperate with industrial partners in developing stable coating and encapsulation processes on our roll-to-roll coater, which can then be transferred to full-scale production equipment.

Concerning perovskite solar cells, we are working on different approaches to guarantee adequate long-term stability. In addition to pure perovskite solar cells, we are also developing silicon-based tandem solar cells to make better use of the solar spectrum by reducing thermalization losses. We are also following this strategy with our work on tandem solar cells made by combining crystalline silicon with III-V absorber materials or silicon nanocrystalline materials with adjustable band gaps. In doing so, we apply particularly our photon management concepts to ensure good current matching between the sub-cells.

Milestones in 2017

» Photonic structures (diffractive gratings) contribute in a III-V // Si three-junction solar cell to a current increase of 1.1 mA/cm². As a result, the efficiency value of the solar cell is increased by 1.9 % (absolute).
» Very clean laboratory taken into operation for the development of perovskite-silicon tandem solar cells, equipped with a glovebox connected to an evaporation chamber.
» Perovskite solar cell with a stabilized efficiency value of 18 % for use in a perovskite-silicon tandem solar cell produced with a low-temperature process.
» Certified efficiency value of 12.6 % for a monolithic perovskite solar cell with graphite electrode.

1 *Semi-transparent organic PV module.*

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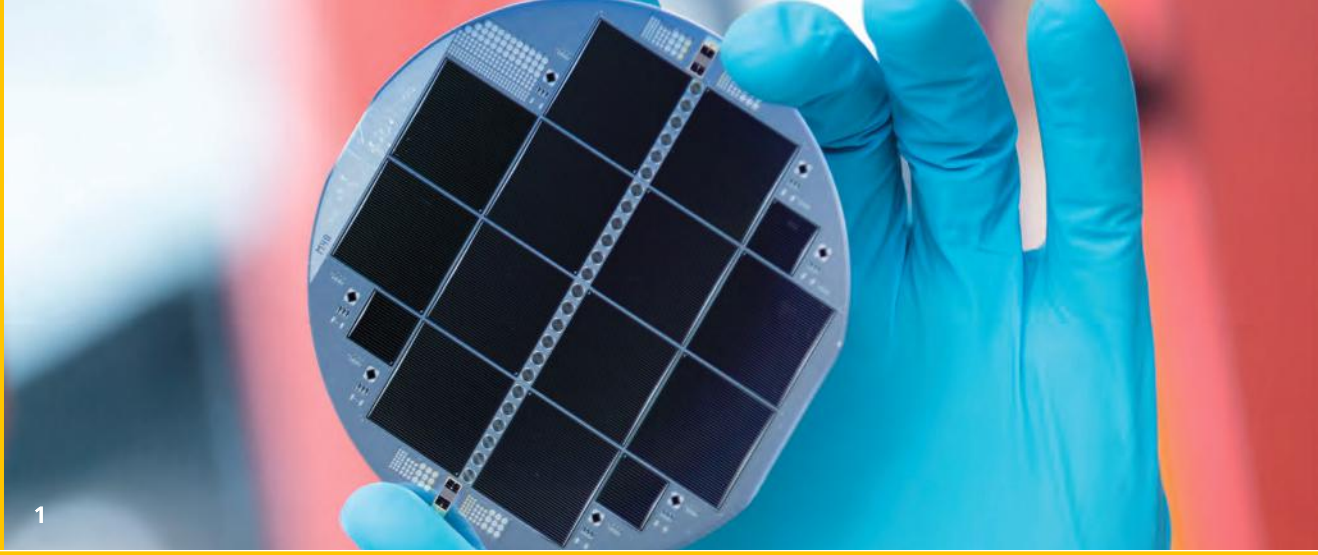
More information on projects:
www.ise.fraunhofer.de/en/research-projects/1-03



Crystalline Si and III-V Compound Semiconductor Multi-Junction Solar Cells

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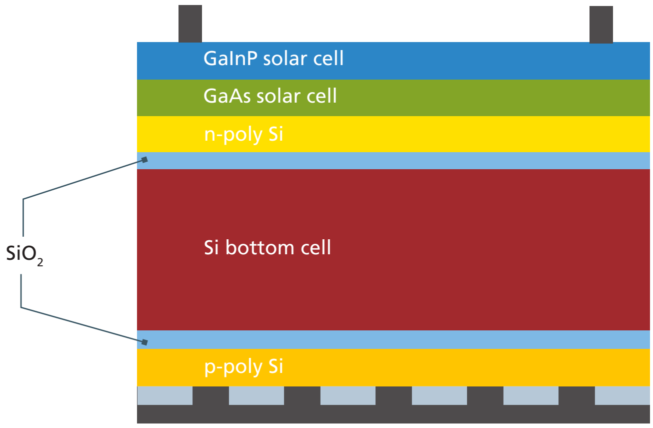
The development of silicon solar cells has made remarkable progress within recent years. Efficiency values of up to 26.7 % are now achieved in the laboratory and more than 22 % in the industry. The theoretical limit of the efficiency value of silicon (29.4 %) is thus drawing closer and closer. In order to increase it also in the future and thus to further reduce the costs for photovoltaically generated electricity, alternative cell architectures are needed.

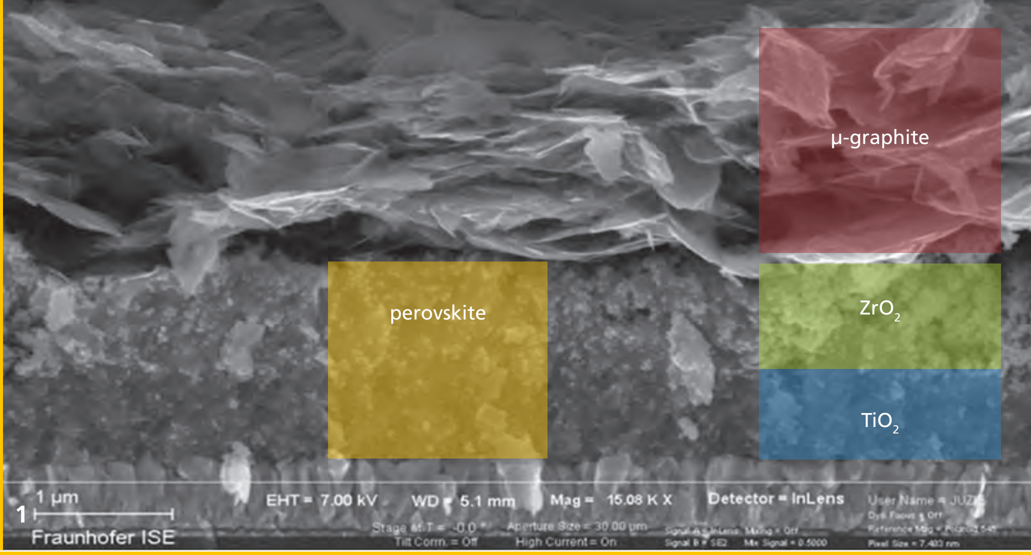


Graph: Schematic representation of the III-V // Si multi-junction solar cell. Details are shown only for the silicon solar cell.

1 *III-V // Si multi-junction solar cell prepared at Fraunhofer ISE on a wafer with 100 mm diameter.*

A fundamental limit for solar cells with only one band gap is the relatively poor exploitation of the broadband solar spectrum. By using multi-junction solar cells with several band gaps, the associated losses can be minimized, allowing higher efficiency values to be reached. Due to their very suitable band gap and the cost-effective production technology which has already been upscaled, silicon solar cells are a good choice for the bottom cell in a tandem configuration. Perovskite or III-V compound semiconductors are suitable for the upper sub-cell with a larger band gap. Fraunhofer ISE is developing e. g. a combination of a GaInP (1.9 eV) upper cell and a GaAs (1.4 eV) middle cell on a Si (1.1 eV) bottom cell (see graph).

For our multi-junction solar cells, we are following the approach of a monolithic configuration, because this greatly simplifies the connection of single cells within a module. As direct growth of the III-V materials on silicon is still a challenging research subject due to the different lattice constants, we apply the wafer-bonding process to connect the sub-cells, in which two semiconductors are permanently bonded to each other by applying pressure. Overall, we can achieve efficiency values (non-concentrated sunlight, AM 1.5g) of 33.3 % for a monolithic III-V // Si multi-junction solar cell with this cell concept. This value is listed in the "Solar Cell Efficiency Tables" in "Progress in Photovoltaics" as the highest value for a 2-terminal multi-junction solar cell with silicon.



Printable In Situ Perovskite Solar Cells

Dr Andreas Hinsch | Phone +49 761 4588-5417 | emergingpv.dye@ise.fraunhofer.de

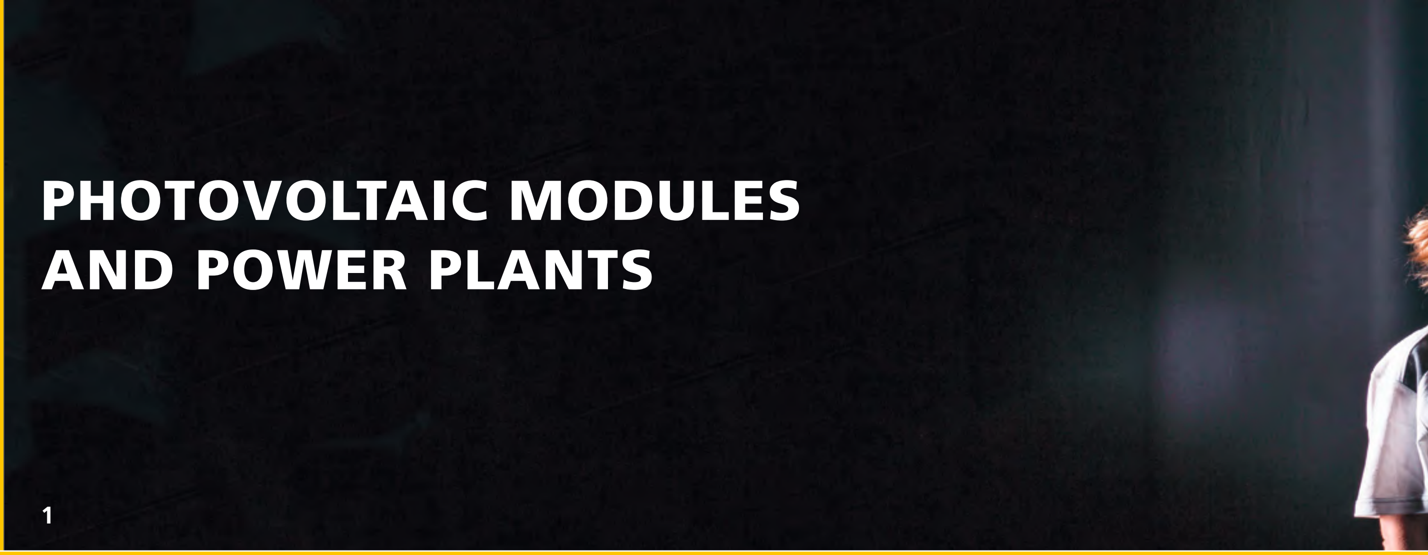
The traditional production of silicon-based solar modules works on the principle that initially solar cells are produced in wafer formats and subsequently they are connected and laminated to form a complete module. An alternative to this is a concept in which the solar cells are created in situ within the module. Savings in the production costs can be expected as a result. Fraunhofer ISE is investigating soluble, photovoltaically active perovskite salts of the type AMX_3 as particularly suitable materials for the in situ concept.

The goal of current projects is to develop printable nano-porous electrode layers to deposit and connect the perovskite crystals and to optimize the deposition process, in order to demonstrate high solar efficiency values in the completed cells. We optimized screen-printed porous layers of TiO_2, ZrO_2 and micronized graphite (µ-C). The thickness of the photovoltaically active zone within the first two layers is less than a micrometer (Fig. 1).

Control of the deposition process for the perovskite crystallites in the interior of the porous electrodes is decisive for the solar efficiency value. During the reporting period, uncontrolled crystal growth, as occurs during the previously usual chemical precipitation of ions from a solution, was prevented. By applying reversible adsorption of a polar gas, we succeeded in converting the perovskite into a molten salt at room temperature and thus to fill the pores. The controlled desorption of the gas causes physical recrystallization from the melt and results in a homogeneous growth process. Photoactive layers that are produced in this way feature a long charge-carrier lifetime, which is reflected in the high photovoltage of 1 Volt and the solar efficiency value of 12.6 % which has been certified for laboratory cells with graphite electrodes. The methods that have been developed for in situ perovskite solar cells on small areas and the results obtained form the basis for demonstrating the upscaling potential. An important milestone was achieved with the development of the molten perovskite salt. We have already produced our first larger test modules to investigate the crystallization behavior and long-term stability. In addition to a possible application of in situ perovskite solar cell in photovoltaics, the very good photoluminescent and electroluminescent properties are being investigated with a view to potential usage in optoelectronics.

1 *SEM image of the cross-section of an in situ perovskite solar cell.*

PHOTOVOLTAIC MODULES AND POWER PLANTS


1

122
Total staff

8
Journal articles and contributions to books

19
Lectures and conference papers

6
Newly granted patents

Module technology transforms solar cells into durable products for safe operation in PV power plants. Our Module-TEC – Photovoltaic Module Technology is equipped with a wide range of modern processing and analytical platforms for connecting and laminating solar cells, especially for material testing, as well as developing products and processes. We apply measurement and simulation to analyze cell-to-module balances (CTM).

The reliability of modules is tested by the team in our accredited TestLab PV Modules for certification according to IEC 61215 and with respect to particular climatic loads and specific degradation risks. We support our clients in qualifying materials and offer comprehensive analyses of degradation and damage to modules. Highest accuracy is also offered by our accredited calibration laboratory, CalLab PV Modules, which is the internationally leading laboratory in this field, with its measurement uncertainty of better than 1.3 % 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. We develop reliable, probabilistic methods to predict the performance of PV systems.

Based on our expertise in photovoltaics, building science and energy supplies for buildings, we offer solutions to integrate photovoltaics into the building envelope. Our team also develops customized solar modules for special applications such as integration into vehicles and consumer devices.

Milestones in 2017

- » Development of the "SmartCalc.CTM" software for comprehensive analysis and optimization of the effects which appear during the integration of solar cells into solar modules (Cell-to-Module).
- » Accreditation of our CalLab PV Modules calibration laboratory for 1.3 % measurement uncertainty in the power measurement of photovoltaic modules.
- » Establishment of a state-wide measurement network in Baden-Württemberg for real-time monitoring of photovoltaic generation by TransnetBW and Fraunhofer ISE.
- » Yield analysis for a PV power supply for utility vehicles e. g. refrigerated trucks, with measured radiation data.

1 *Test facility developed by Fraunhofer ISE for the calibration of bifacial PV modules.*

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

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Forecasting of Solar Irradiance and Power
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PV For Mobility
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Selected Projects in 2017

- SPEISI – Safety and reliability of PV Plants with storage systems with special consideration of fire risks and extinguishing strategies
- ALRPO – Self-learning algorithms for PV power forecasting as an instrument for decentralized energy management
- PV Live – Operational delivery of solar irradiance and simulated photovoltaic power data to Transnet BW

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

Photovoltaics on Commercial Vehicles

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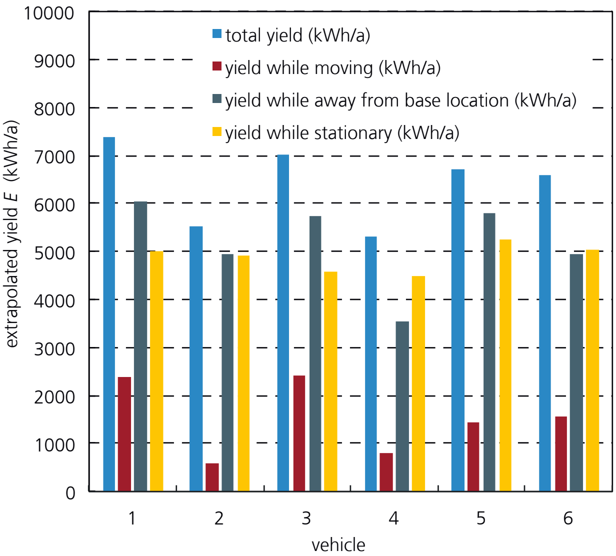
In the new research area, "PV For Mobility", Fraunhofer ISE is concentrating its activities on integrating photovoltaics into vehicles and transport routes. The rapidly falling costs for solar cells open up new application fields in (electro-)mobility. For example, the large roof areas of commercial vehicles are suitable for application-optimized, lightweight PV modules to reduce CO_2 emissions in the transport sector or to increase driving ranges.



Graph: Normalized yield data for one year for the investigated vehicles, assuming a PV-active roof of a 40 t semi-trailer.

1 *Some of the tracked routes superimposed onto a solar irradiance map of Europe. © European Union, 2012 PVGIS (map) / topae / shutterstock (truck)*

In order to determine this potential, Fraunhofer ISE, with support from Fraunhofer CSE in Boston and in cooperation with three freight companies, equipped six trucks with a specially developed irradiance measurement unit. The measurement data comprise one-minute averages of irradiance, generated power, temperature, position and speed. Over a period of up to 15 months, comprehensive and valuable data were acquired along real transport routes in Central and Southern Europe as well as in North America.

From the data, it became evident that operation on commercial vehicles occurs under significantly different conditions to those experienced in conventional rooftop or ground-mounted systems. For example, the average module temperature was 22.6 °C (with a minimum of -14.0 °C and a maximum of 66.6 °C), and the positive effect of airflow on the module temperature was quantified. Furthermore, analysis of the data revealed that the average irradiance was about 277 Wm^{-2}. Another result of this measurement campaign was that the vehicle with the highest yield potential would have generated a calculated energy of 7395 kWh/a, while the vehicle with the lowest yield would still have delivered 5297 kWh/a. Converted to the equivalent amount of diesel, this corresponds to savings of 1513 litres to 2113 litres per year. Further important information about the lengths of time spent driving and stationary, mobility profiles and concerning PV system design was gathered.

The results of this measurement campaign enable us to carry out targeted development and qualification of PV technology for applications on vehicles in cooperation with partners from the mobility sector.

Satellite Data and Real-Time Solar Radiation Measurements for PV Power Upscaling

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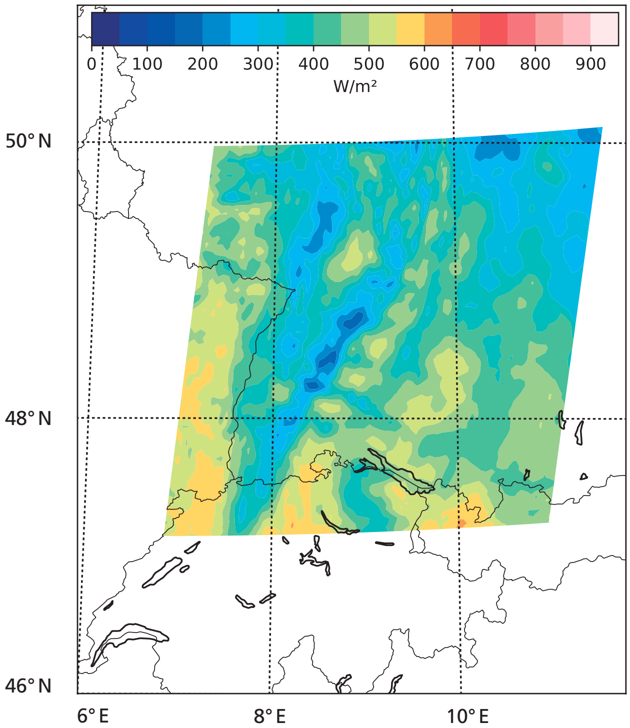
Photovoltaics already plays a fundamental role in the German energy system. With an installed PV power in Germany of currently around 42 GW, already more than 50 % of the electric load can be covered by solar electricity at midday on sunny days. However, the generation of PV electricity depends on the sun's position and the weather. In order to guarantee a reliable and cost-effective power supply also in future, reliable PV power upscaling and prediction are becoming increasingly important. On the one hand, these calculations are the basis for marketing PV electricity on the electricity exchange. On the other hand, grid-critical situations can already be recognized early on the basis of prediction, and corresponding corrective measures can be taken. Altogether, better predictions contribute to lower costs in the grid integration of PV electricity.

In energy meteorology, we are developing algorithms to predict PV power for forecast horizons from a few minutes to several days. The starting point for a reliable prediction is the assessment of the current PV power in real time. However, this is determined for only part of the PV systems installed in Germany. This means that the total power fed into the control areas of the transmission system operators is not known directly. To date, the actual amount of PV power fed in is estimated as well as possible from the available information with PV power upscaling. Fraunhofer ISE has developed an innovative approach for PV power upscaling in the "PV Live" project for the transmission system operator TransnetBW.

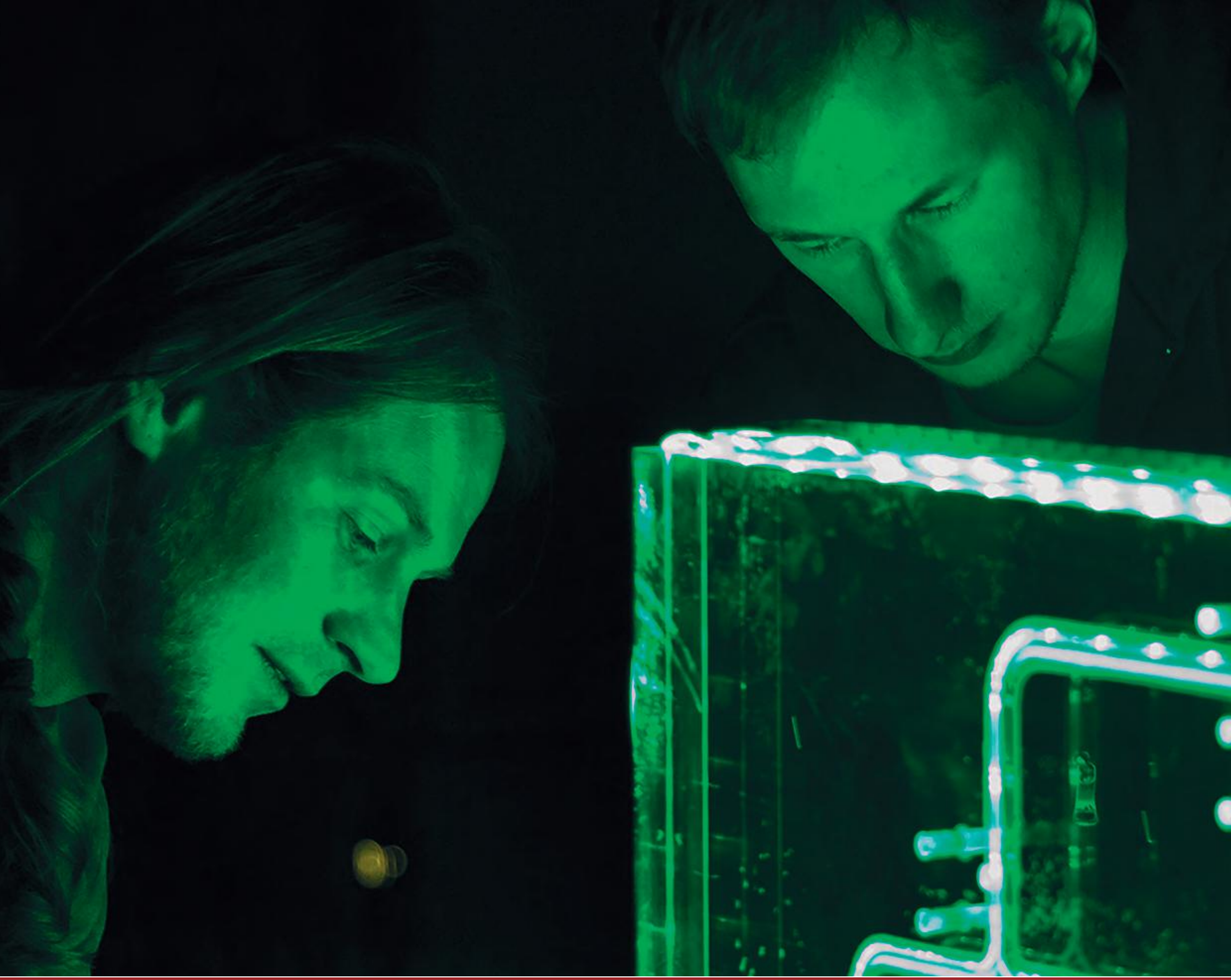
As input data for the upscaling, we supply real-time measured values of the irradiance and simulated PV power values to TransnetBW every minute. To this purpose, a measurement station was developed which is optimized to meet the requirements of PV power upscaling. The measurement stations were distributed over the State of Baden-Württemberg, whereby the distance between neighboring stations is between about 15 and 35 kilometers. These local measurements are complemented by satellite-based solar irradiance maps. We provide these for the entire control area in a 4 km grid at 15-minute intervals. The combination of ground-based measurements and satellite data is intended to enable new upscaling approaches and significantly improve the forecast in comparison to existing approaches.



Graph: Satellite-based irradiance map for the control area of TransnetBW.

1 *Satellite data enable a real-time, finely resolved mapping of the solar irradiance and the fed-in PV electricity. Photo satellite © Meteosat Second Generation (EUMETSAT)*

2 *Measurement stations developed by Fraunhofer ISE, with a pyranometer and silicon sensors oriented in different directions, send updated measurement data every minute.*



ENERGY TECHNOLOGIES AND SYSTEMS

The energy transformation is entering its second phase, not only in Germany but also in many countries that have achieved a similarly high penetration of renewables in their energy supply. The first phase of the transformation was marked by key developments and cost reductions in the conversion of the renewable energy sources, in particular wind, solar and biomass, to electricity. These developments have made it possible that an affordable energy transformation towards a more efficient, sustainable and resilient renewable-based energy system has become conceivable at all. A strong growth in installed capacity over the past years had led to the fact that renewable energy sources supplied 38 % of Germany's electricity in 2017. The heat, transport and industry sectors, however, are lagging far behind. In Germany, we are still heating our buildings for the most part with natural gas and heating oil. The mobility sector relies largely on fossil fuels. In this respect, a holistic integration of renewable energy sources is imminent in the second phase, and with it a much stronger coupling of the electricity, heat and transport sectors. Much speaks in favor for the increased electrification of these sectors. There are numerous applications in which electricity from renewable sources can be used directly and very efficiently, for example, in heat pumps or battery electric vehicles. In areas where it is difficult

i *Measurements on a novel distributor for coolant in a heat pump.*

to use electricity directly, such as heavy-load, ship and aviation transport or also industrial processes, these can be supplied increasingly with renewable, chemical energy carriers. Biomass resources are limited, and therefore hydrogen will play an increasingly larger role here. Renewable hydrogen can be used for reconversion into electricity with stationary or mobile fuel cells or be used directly in industrial processes. Also, hydrogen combined with carbon dioxide can be further converted into renewable synthetic fuels or chemicals for industry.

Since its founding, Fraunhofer ISE has worked on many technologies and projects relevant for the upcoming second phase of the energy transformation. The division "Energy Technologies and Systems" specializes in these topics in its business areas of Solar Thermal Technology, Building Energy Technology, Hydrogen Technologies and Energy System Technology. Out of the many projects and results presented on the following pages and on our website, we mention two main developments here: First of all, the accreditation of our broad-based test and development center for heat pumps has been successfully completed according to the DIN EN ISO / IEC 17025. Besides the scientific and development services, we can now extend our offer to include certification tests. Secondly, in 2018 we will inaugurate our extended and enlarged Center for Power Electronics and Sustainable Grids at its new location on the Zinkmattenstrasse in Freiburg. In the new facilities, we can develop, analyze and test systems and components up to 40 MVA for both the low and medium voltage levels.

SOLAR THERMAL TECHNOLOGY

The use of solar thermal energy is essential for the transformation of the German energy system in the thermal sector. Fraunhofer ISE is contributing to this with cost-effective materials, manufacturing processes and components, as well as macro-economically and micro-economically optimized complete systems.

In our work on solar thermal technology, we are concerned with optics and surface technology to make better use of solar radiation. We investigate low-temperature solar thermal systems, with water or air as the heat-transfer medium, to heat domestic hot water, buildings and industrial processes more efficiently. Combined photovoltaic-thermal collectors allow to generate electricity and heat simultaneously from the same area. We are working on façade-integrated and roof-integrated solutions which offer excellent architectural options to integrate solar thermal systems into the building envelope and use them multi-functionally. With concentrating collectors, temperatures of several hundred degrees can be reached. We are researching how electricity, heat for industrial processes and steam and driving heat for sorption chillers can be generated in this way in large solar thermal power plants. Energy-efficient thermal storage units in the high and low temperature ranges are another subject of our work, as they are central for our future energy system. In addition, we work on thermally driven, membrane-based processes to purify or concentrate residual materials in industrial waste water or to obtain drinking water by desalinating sea water.

76
Total staff

20
Journal articles and contributions to books

27
Lectures and conference papers

4
Newly granted patents

Fraunhofer ISE possesses profound expertise in materials science, component design, characterization and testing procedures, theoretical modelling and simulation, systems control and systems development. Furthermore, the Institute has extensive experience in a wide range of applications.

Milestones in 2017

- » Commissioning of an innovative heating supply network with a central heat supply and distributed solar thermal energy supply for the efficiency-optimized combination of heat, power and solar thermal energy in an integrated thermal network.
- » 2 – 17 % energy-economic potential for solar heat identified in urban heating supply systems in various countries (IEA SHC Task 52).
- » Highly efficient prototypes of a combined photovoltaic-thermal collector with an optimized low-emissivity coating tested successfully.
- » Proof of the longevity of commercially available, high-quality collectors (“SpeedColl”, BMWi funded).
- » Experimental proof of good thermal stratification in a high-temperature, single-tank storage unit based on molten salt.
- » New procedure to determine the performance of linearly focussing collectors and solar arrays, based on dynamic operating data.

1 *Parabolic trough collectors at the solar thermal power plant Andasol 3. Here, Fraunhofer ISE is testing devices that automatically measure the degree of soiling on mirrors and is also using the operating data of the power plant to validate its own software.*

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Selected Projects in 2017

- RAISELIFE – Raising the lifetime of functional materials for concentrated solar power technology
- SolVapor – Integration of solar collectors in industrial process steam plants
- ZeKon in situ – Development of a certification concept for large solar thermal systems based on in situ measurements with the aim of market entry at lower costs
- IKI Solar Payback – Technical support to the development of contents and activities in project Solar Payback
- MENA CSP KIP – Middle East and North Africa Concentrating Solar Power Knowledge and Innovation Program
- HelioControl – Development of a camera-based calibration and control system with a closed control circuit for heliostat arrays
- MinWaterCSP – Minimized water consumption in CSP plants
- TrustEE – Innovative market-based trust for energy-efficiency investments in industry
- INSHIP – Integrating national research agendas on solar heat for industrial processes
- EnWiSol – Solar thermal energy in the municipal energy supply; energy-economic analysis and demonstration project Freiburg-Gutleutmatten

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

Solar Thermal Power Plants with Low Water Consumption

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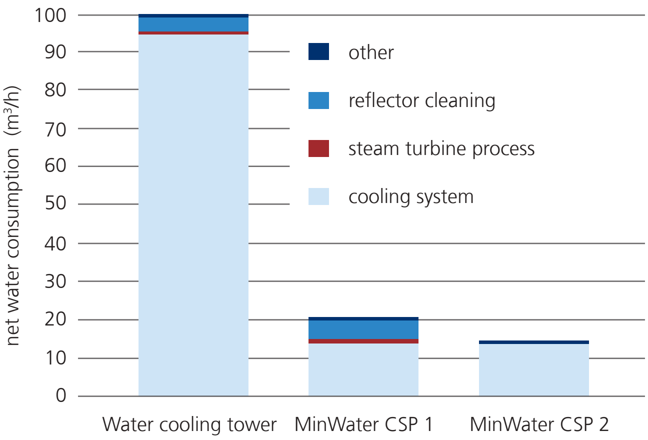
Solar thermal power plants with high-temperature storage allow to decouple solar radiation and power generation and thus provide a dispatchable electricity generation and supply in the renewable energy mix. As solar thermal power plants are often located in arid regions which are not only sunny but also dusty, the associated yield reduction due to local dust deposition and the cost of cleaning are important topics. Particularly in regions lacking in water, it became evident that innovative solutions were needed which could significantly reduce the water consumption of solar thermal power plants. At Fraunhofer ISE, we are working on technology to increase the efficiency of the power plants and are developing methods to reduce the water consumption.



Graph: Water cooling compared to hybrid cooling without (MinWaterCSP 1) and with internal water recycling (MinWaterCSP 2).

1 *"AVUS" measurement system for automated monitoring of soiling in solar thermal power plants.*

2 *Soiling measurement in a solar thermal power plant with the "pFlex" measurement instrument developed at Fraunhofer ISE.*

We cooperate with industrial partners to develop equipment and methods to determine soiling so that we can increase the performance of power-plant operation and predict and optimize the cleaning cycles. Methods based on optical measurements characterize the soiling as a function of time reliably and accurately. Prototypes of the "AVUS" soiling measurement instrument for automated detection of the reduced reflectance of solar reflectors were installed in the "Andasol 3" power plant in Spain (Fig. 1). In combination with other meteorological data, the methods developed at Fraunhofer ISE will contribute to improved operation and cleaning strategies in future. The portable "pFlex" reflectrometer is suitable for quick, manual measurements in situ at the solar array (Fig. 2). Further developments in future will enable large-area detection of soiling across the solar field.

In order to reduce the water consumption in the entire solar thermal power plant, we work at Fraunhofer ISE on reducing the cooling water consumption, on water-saving cleaning concepts and on water treatment for re-use. Another important component to reduce water consumption is the integration of water management into our simulation tools (e. g. ColsimCSP). The development of comprehensive water management plans (see graph) contributes, in parallel to the technological development, to making the systems less dependent on the availability of high-quality water sources.

Innovative Approaches for Supplying Solar Heat to Buildings

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An essential contribution to the success of the energy transformation can be made by innovative solar heating systems, which provide most of the heat needed for space heating of individual buildings and domestic hot water. Fraunhofer ISE has investigated this type of innovative heating system in the "HEIZSOLAR" project, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). These systems are crucial to meeting the requirements of nearly-zero energy consumption by buildings – as will be demanded in future and is defined by the EPBD (Energy Performance of Buildings Directive) of the EU. The results of Fraunhofer ISE in the "HEIZSOLAR" project demonstrate how solar thermal building heating can be implemented cost-effectively.

Solar thermal approaches are promising not only for individual buildings but also for buildings within a district heating concept. In the "ENWISOL" project, supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), distributed thermal systems are connected within a thermal grid with a central heating supply based on combined heat and power (CHP) generation. One of the ideas behind this concept is to reduce the thermal losses of the thermal grid significantly during periods of low demand in summer. During this time, the grid can be deactivated completely for some periods, while the solar thermal systems supply all the heat that is needed. Another feature of such a concept is that during the anticipated periods with an electricity surplus in future summers, the heat supply from the CHP plant, which is not economic then, can be replaced by solar heat.

In the context of transforming the German energy system, the question about which renewable technology will succeed will be decided not only by the aspect of micro-economic competitive advantages but also by macro-economic cost considerations, social acceptance and the political will to support certain technological options. For the success of solar thermal heating systems, it is decisive to reduce the costs of the systems for the users.

When the entire value chain is examined, it becomes evident that significant costs originate outside the actual manufacturing process of the components. Thus, innovative approaches are needed, which take not only the cost optimization of components into account. Together with RWTH Aachen, Fraunhofer ISE is developing innovative methodology within the "TEWISOL" project – which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) – to analyze the entire value chain. Value creation over the whole chain is to be investigated and optimized, starting with product development, continuing with production processes by manufacturers of components and systems, through to system installation and commissioning by tradespeople. This will indicate which technical simplification and standardization of components and systems, which changes in the processing sequence and which product complexity correspond to market expectations and simultaneously offer maximum cost advantages.

1 *"SolarAktivHaus" with a solar thermal fraction of 100 % in Kappelrodeck, Germany.*

BUILDING ENERGY TECHNOLOGY

More than 40 % of the end energy demand in Germany is caused by the building sector. 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 on 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 to reduce the demand for space heating and space cooling include new glazing technology such as switchable coatings and appropriate controls for solar-shading systems. Other concepts use the building envelope also for active energy conversion, e. g. building-integrated photovoltaics (BIPV). For this application, we have developed colored cover panes, which offer architectural design freedom while retaining good electricity-generating performance.

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 cooling circuit, through equipment and system development, to quality assurance in practical operation.

Holistic energy concepts and their planning with digital methods such as Building Information Modelling (BIM) are becoming increasingly important, particularly when high, energy-relevant quality in planning and building operation is to be achieved with systems based on renewable energy sources. 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.

194
Total staff 194

34
Journal articles and contributions to books

38
Lectures and conference papers

4
Newly granted patents

1 *Coating to intensify processes in dehumidification and heat-pump technology. Adsorbents are deposited onto heat exchangers, applying technology that has been patented by Fraunhofer ISE.*

Milestones in 2017

» Newly developed, colored cover panes for PV modules, which can provide attractive building cladding as well as generating electricity.
» Analysis of the central role of heat pumps in renovating existing medium and high-density housing: »WP Smart im Bestand« (BMWi funded).
» Development of a propane heat pump with significantly reduced fuel consumption (76 g/kW heating power) in the “Green Heat Pump” project (EU funded).

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Selected Projects in 2017

- CRAVEzero – Cost reduction and market acceleration for viable nearly zero-energy buildings
- EnWiSol – Solar thermal energy in the municipal energy supply; energy-economic analysis and demonstration project Freiburg-Gutleutmatten
- FlexGeber – Demonstration of flexibility options in the building sector and their interaction with the energy system in Germany
- LowEx-stock Analysis – LowEx-concepts for the heat supply of existing multi-family houses
- synGHD – Synthetic load profiles for efficient energy supply planning for non-residential buildings
- follow-e2 – Power-saving functional surface coating of polymer materials for membrane architecture

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

Attractive and Cost-Effective BIPV Building Products

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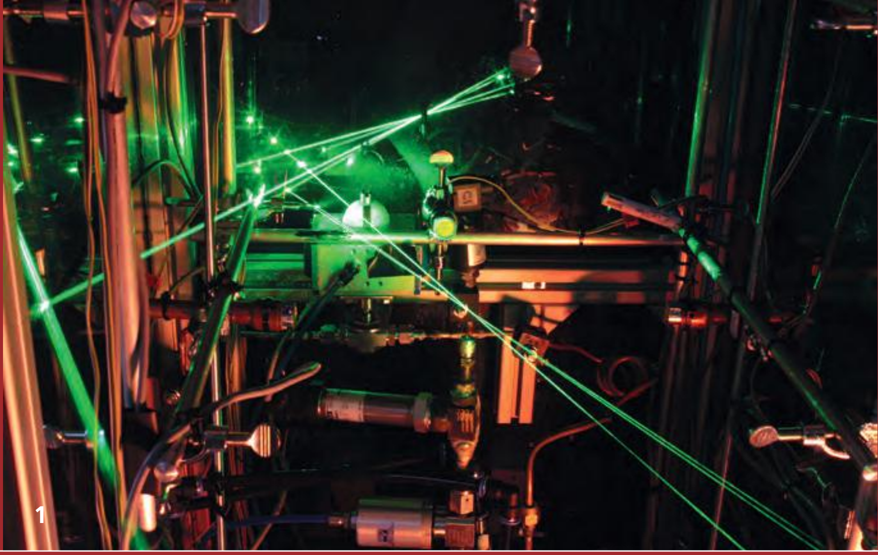
Zero-energy buildings and plus-energy buildings with building-integrated PV (BIPV) are important components of the energy transformation. However, there is consensus that solar electricity from PV systems, not only with respect to individual buildings, will be a fundamental pillar of the future energy supply. Studies from Fraunhofer ISE show that in a renewable energy system for Germany, PV systems with a power rating up to 300 GW Peak would have to be installed, which corresponds to an area of up to 36 m^2 per inhabitant in Germany. In a doctoral thesis completed in 2017, it was demonstrated that the economically usable area on building envelopes greatly exceeds this required area, and that not only roofs but also façades offer relevant potential area. Due to the prices for photovoltaics, which have fallen steeply yet again, the additional costs for building products with PV functionality are often amortized within a few years. In order to achieve a breakthrough in the mass market for BIPV, the costs must be reduced further and also the appearance of BIPV products must become more attractive.

Fraunhofer ISE is pursuing various approaches to achieve these goals. On the one hand, we filed a patent in 2017 for a colored coating on BIPV modules with highly saturated colors, good stability of the color impression for different viewing angles and only slight losses in electric efficiency (well below 10 $\%_{rel.}$). The fact that the PV module structure is no longer visible makes it much more architecturally attractive (Fig. 1). The approach is based on colored photonic structures imitating those on iridescent morpho butterfly wings. The color effect is created by the interaction between geometric structures and interference films on the inner surface of the module cover pane. The coating can be produced by cost-effective industrial coating processes.

In addition, we are working on standardized BIPV products. In the "StandardBIPV" project, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), we have carried out a detailed analysis of the building stock in Germany to identify building categories which can be renovated with prefabricated and standardized BIPV façades. In the project, for example, the "factory and warehouse" category will be investigated in detail, which in Germany alone accounts for more than 100 million m^2 of façade area.

A further approach to reduce costs is to simplify project planning. In systems with customized BIPV modules and more complex shading situations, detailed planning is necessary to ensure that the system yield is reliable and high. Here, Fraunhofer ISE supports the planner directly on the one hand, and on the other, it works in the "SolConPro" project, supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), to integrate solar-active façades holistically into the planning process by applying the methodology of Building Information Modelling (BIM).

1 *The brilliant, individually adaptable colors of these modules and their high efficiency values are unique in this sector.*



Heat Pumps with Climate-Friendly Refrigerants

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Increased usage of heat pumps in building technology and industry is essential for successful implementation of the energy transformation. Nevertheless, the market growth of this efficient technology has not yet met expectations. To date it cannot make any significant contribution toward reaching energy-saving goals. The reasons are the challenging requirements of the market concerning cost efficiency, noise emission, safety, integrated functions and design as well as environmental friendliness. To address these challenges, further development of the equipment is needed.

Fraunhofer ISE is investigating these questions while developing compression and sorption processes for heat pumps, driven by electricity, gas or waste heat. In both processes, environmentally friendly refrigerants such as natural refrigerants, e. g. propane, water or methanol and hydrofluoro-olefins (HFO), are used.

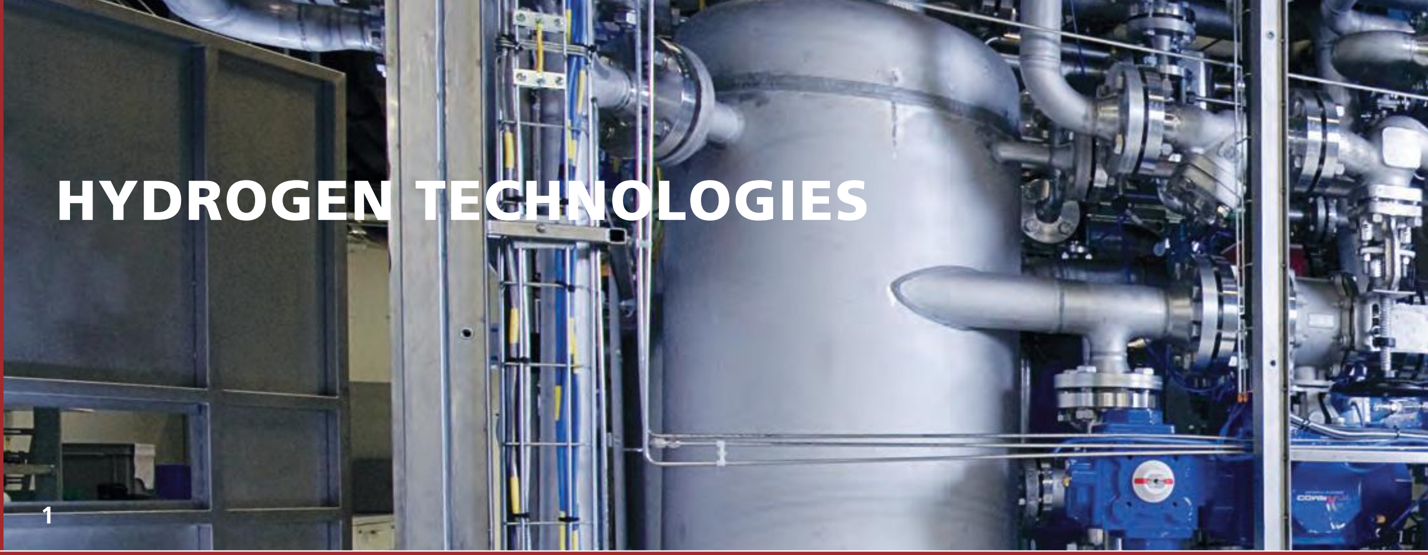
In addition to energy-related optimization of the compression circuit, the development of safety concepts is a key challenge, so that flammable refrigerants can be used on a broader basis. Procedures to detect and prevent leakage are being developed in the laboratories of Fraunhofer ISE. Essential components are being tested and optimized with focus on refrigerant charge reduction and the the interaction between components an new refrigerants.

The development of a propane heat pump in the EU funded "Green Heat Pump" project represents a milestone in this direction. With this design, which was developed together with partners, the required amount of refrigerant was reduced from typically 611 g/kW in air-water heat pumps with the corresponding system power to 76 g/kW heating power. The basis for this was a modified design for all involved heat exchangers and the compressor oil sump, as well as the usage of propane as the refrigerant.

In adsorption processes for heat pumps and cooling systems, water is an eminently suitable, environmentally friendly refrigerant due to its material properties. The development of suitable materials, heat exchangers as well as system concepts at Fraunhofer ISE is the central topic in a project that is financed by the Fraunhofer Zukunftsstiftung (Foundation for the Future). The future results of the development are expected to be thermally driven heat pump modules which feature a power density that is five times greater than the state of the art, so that gas-driven, wall-mounted heat pumps can be implemented.

1 *Laser-Doppler anemometric measurements to analyze the spatial velocity distribution of propane flowing out through a well-defined opening. The investigations reveal the spatial and temporal distribution of refrigerant in the room and support the development of safety concepts.*

HYDROGEN TECHNOLOGIES



With our activities in the area of Hydrogen Technologies, we offer R&D services addressing the generation, conversion and storage of hydrogen. In electrochemical generation of hydrogen, we are concentrating on electrolysis of water in polymer-electrolyte membrane electrolysers (PEM). We carry out multi-scale physical simulation and electrochemical characterization of cells and stacks. In addition, we construct functional working models from the cell stack up to fully automated complete systems.

We develop fuel cell systems for real outdoor conditions, especially for automotive technology and decentralized stationary systems. Our research encompasses the development, simulation and characterization of single cells, cell stacks and systems as well as the testing of peripheral and cell components under extreme climatic conditions.

We have many years of experience in the chemical engineering and process technology of thermochemical processing of fossil and biogenic fuels. These processes include reforming and pyrolysis, as well as the synthesis of liquid fuels from hydrogen and CO_2. We develop processes to synthesize sustainable liquid fuels or also chemical building blocks.

Water electrolysers, being distributed and controllable loads, present an increasingly valuable control option for grid operators to quickly adapt electricity generation and consumption and also to stabilize the grid frequency. Hydrogen as a fuel for fuel cell vehicles creates the link between the energy economy and zero-emission mobility.

84
Total staff

12
Journal articles and contributions to books

13
Lectures and conference papers

1 *Test facility to measure a PEM electrolyser stack with currents of up to 4000 A to produce hydrogen.*

Milestones in 2017

- Construction of a municipal vehicle powered by fuel cells.
- Hydrogen supply system established to feed regeneratively produced hydrogen from Fraunhofer ISE into the natural gas network of the badenova utility in Freiburg.

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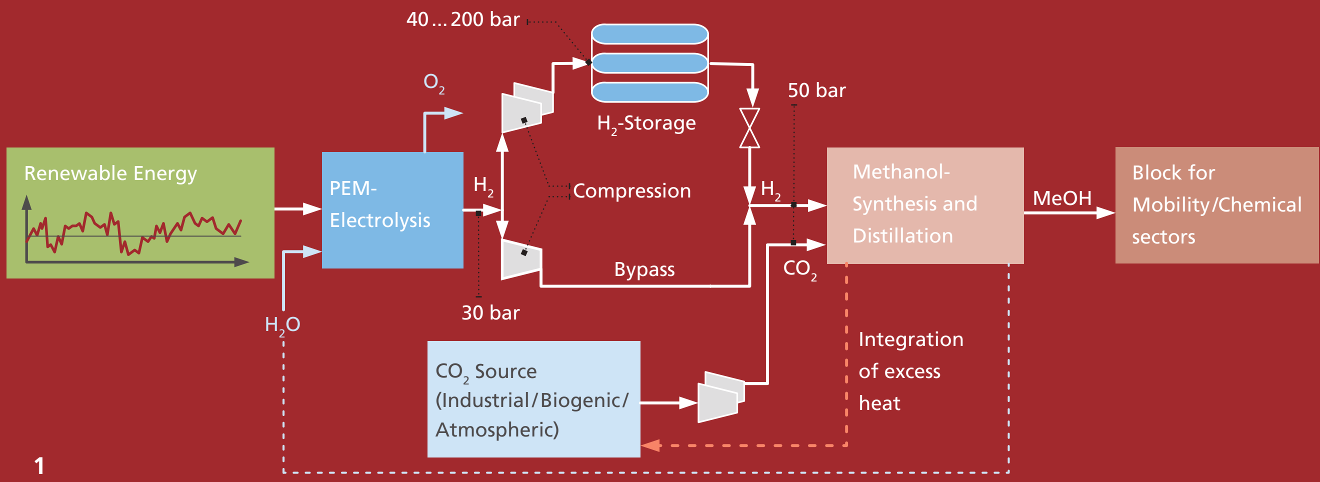
Selected Projects in 2017

- SSoHMuSDaSS – State-of-health modelling and simulation as well as diagnosis of fuel cells, stacks and systems
- AutoStack-CORE – Automotive fuel cell stack cluster initiative for Europe II
- ELAAN – Electric drive train for work and utility vehicles

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/4-00



Economic and Ecological Evaluation of Power-to-Liquid Processes

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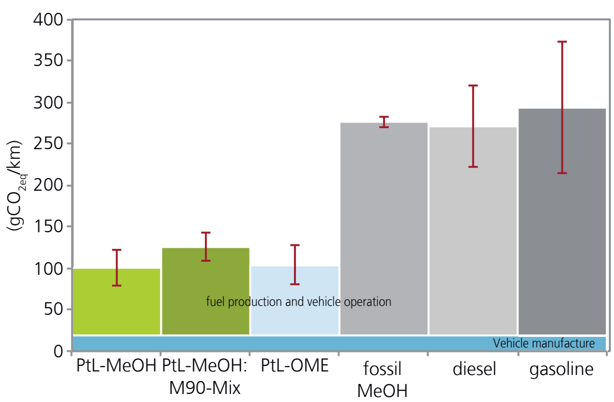
The synthesis of liquid fuels based on carbon dioxide (CO_2) and renewably generated hydrogen (H_2) from electrolysis (Power-to-Liquid, PtL) will make an important contribution to a forthcoming sustainable energy system, which efficiently connects the energy, mobility and industrial sectors. At the same time, a PtL system, with its abundance of possible products such as methanol (MeOH), dimethyl ether (DME), oxymethylene ether (OME), etc., unites several sustainable features. These include e. g. the recycling of CO_2 as an important component in closing the carbon cycle, the production of renewable fuels with high energy density and the production of sustainable platform chemicals (Power-to-Chemicals). When the PtL products are used as fuels in the transport sector, the appreciable reduction of CO_2, NO_x and respirable dust emissions due to potentially environmentally friendlier production and improved combustion properties is a further advantage.

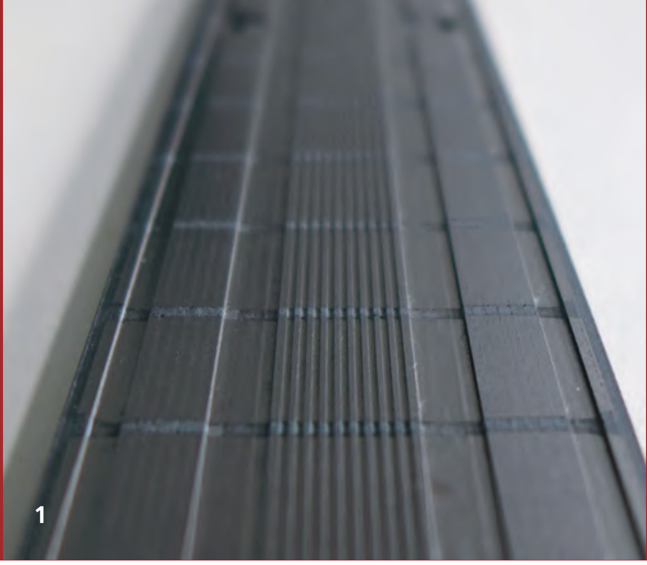


Graph: CO_2-equivalent emissions per km travelled for various fuels: PtL methanol and PtL OME from a wind energy / PV electricity mixture and CO_2 from biogas, PtL methanol / gasoline mixture (90 vol-% MeOH), fossil MeOH from synthesis gas via steam reforming of natural gas, conventional fuels; indicated uncertainty tolerances are based on the relevant possible production scenarios or deviations found in published studies.

1 *"Power-to-Liquid": here with sustainable methanol as the target product, based on renewable energy, water electrolysis and captured CO_2.*

Fraunhofer ISE is evaluating the PtL process for various application cases with respect to its economic viability and potential sustainability. For the ecological evaluation, we are subjecting the PtL process to a holistic lifecycle analysis (LCA). The results are compared, for example, with those for gasoline and diesel recarding use as fuels in combustion engines. We apply a well-to-wheel approach and include the vehicle manufacturing in the evaluation. It became evident that PtL-based fuels emit significantly less CO_2. Furthermore, it was revealed that the fuel production phase has a particularly large impact on the CO_2 footprint.

For a complete systems analysis, we extend the results of the LCA investigations with a comprehensive economic analysis. This showed that electrolysis should be operated with a high utilization factor and feature high energy efficiency, a long lifetime and the highest possible materials efficiency. In this way, the levellized cost of PtL (MeOH) in Germany could be reduced from 800 – 1700 €/t (MeOH) currently (corresponding to 1.29 – 2.74 €/l gasoline equivalent) to < 550 €/t MeOH (< 0.89 €/l gasoline equivalent) in the future. If markets outside Germany are also taken into account (e. g. Norway or Chile), significantly lower production costs could be achieved. Thus, PtL processes could make a significant contribution to reducing greenhouse gas emissions, while simultaneously offering promising economic perspectives.



Performance and Aging Behavior of Fuel Cell Components

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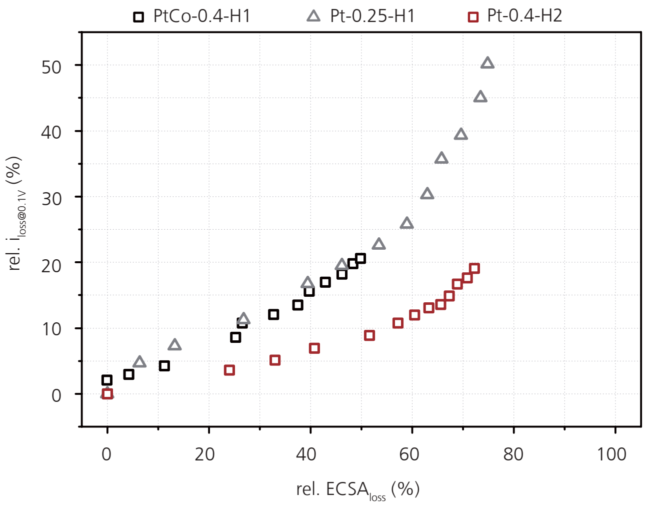
The heart of an automotive fuel cell is the membrane electrode assembly (MEA), in which the electrochemical energy conversion of hydrogen and atmospheric oxygen to electricity, heat and moisture takes place. The MEA must be designed in a way that such reaction gases can diffuse easily to the catalyst, the electrons and the protons can be conducted efficiently and the product water can be transported quickly away from the porous layer. The interaction of these processes determines the performance and efficiency of the fuel cell. At the same time, a high stability of the catalyst, the morphology and the composition of the MEA are to be achieved in order to guarantee minimal aging of the components.

For the analysis independent of specific cell geometries and operating modes, Fraunhofer ISE uses differential test cells and internationally established or customized test procedures. The application of differential test cells ensures that homogeneous operating conditions are established over the entire active area, so that the effect of variations in the surrounding conditions becomes negligible. Efficient analysis of the material properties is possible by the use of various electrochemical in situ methods such as polarization curves, electrochemical impedance spectroscopy, cyclic voltammetry, linear sweep voltammetry and limiting current density measurement. This allows us to investigate the influence of different electrode compositions and production methods e. g. on the aging behavior (see graph).

1 "Along-the-channel" test cell to characterize fuel cell components with realistic channel / wall configurations and operating conditions.

2 Laboratory to characterize fuel cell components.



Graph: Loss of limiting current density at 0.1 V cell voltage i_{loss}@0.1V in relation to the loss of electrochemically active surface area (ECSA) of a platinum and platinum-cobalt (PtCo) catalyst system. The course of the platinum loading of 0.4 and 0.25 mg/cm² and the two manufacturers (H1/H2) show the influence of manufacturing on the aging process.

The evaluation of cell materials under realistic stoichiometric and operating conditions is carried out in our "along-the-channel" test cell (Fig. 1). The latter is used to reproduce real channel / end cross-sections and channel lengths. By dividing the test cell into up to 50 segments, the current profiles can be analyzed from the gas inlet to the gas outlet. For a more thorough analysis of the causes of performance losses which occur in the interaction between materials and local operating conditions, impedance spectroscopy can be applied simultaneously to the current density measurement in all segments.

Finally, the materials are characterized in system-relevant operation in large-area automotive cells or cell stacks. This way, we can verify the results in the intended cell and stack designs with system-induced operating parameters.

ENERGY SYSTEM TECHNOLOGY

In its work on Energy System Technology, Fraunhofer ISE optimizes the interaction between energy generation from renewable sources, consumption, storage and electricity grids. To ensure the overall success of the energy transformation, coupling between sectors, e. g. the grid integration of electromobility within the transport sector, represents a further important aspect of our activities.

192
Total staff

21
Journal articles and contributions to books

52
Lectures and conference papers

1
Newly granted patent

Power electronics is one of the key technologies which can contribute decisively to the reconfiguration of our energy supply. It plays an important role in electricity generation from renewable sources, energy storage, dynamic grid control or electromobility. We apply disruptive technology such as power semiconductor components of SiC or GaN to develop significantly smaller, more efficient and less expensive inverters. Electromobility also gains essential advantages in the form of new charging infrastructure, inductive energy transfer systems and compact and efficient on-board transformers. Rail transport and aviation also emit less CO_2 due to new power electronics.

As the load capacity of the electricity grid is reaching its limits in many places, we are working on better grid integration of energy systems. The so-called "grid-supporting operation" of distributed systems depends both on compliance with the required guidelines and on optimal integration of the systems into the energy market. Our analytical models for energy systems provide techno-economically optimal conversion routes for the energy transformation, both at the neighborhood level and also in regional and transnational contexts. As the energy landscape is becoming increasingly digitalized, a further important focus of our activities is on information and communications technology.

Milestones in 2017

- The "C/Sells" project (BMWi funded) is investigating the Smart Grid of the future together with many partners.
- The "REMod-D" transformation studies demonstrate the cost-optimized route to a German energy supply system based on renewable energy.
- In the "NETfficient" project (EU funded), an extremely compact inverter for 1000 kW was implemented in an IT rack.
- Highly integrated concept for PV inverters promises cost reduction.

1 *Photovoltaics and wind energy, the two pillars of our future energy supply.*
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www.ise.fraunhofer.de/energy-system-technology

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Energy System Analysis
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Selected Projects in 2017

- JOSPEL – Efficient passenger comfort system based on the Joule and Peltier effects
- iDistributedPV – Photovoltaics in the Distribution Grid: Smart-Grid solutions for decentralized electricity generation with photovoltaics, electric storage and demand controls
- Kopernikus Project ENavi – System Integration
- MENA CSP KIP – Middle East and North Africa Concentrating Solar Power Knowledge and Innovation Program
- C/Sells – Large-scale showcase in the ‚solar arch' in Southern Germany
- FlexGeber – Demonstration of flexibility options in the building sector and their interaction with the energy system in Germany
- SPEISI – Safety and reliability of PV plants with storage systems with special consideration of fire risks and extinguishing strategies
- ELAAN – Electric drive train for work and utility vehicles
- synGHD – Synthetic Load Profiles for Efficient Energy Supply Planning for Non-Residential Buildings

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

Power Electronics and Grid Technology in the Multi-MW Range

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As the electricity grid is extended and reconfigured for the energy transformation, the application fields for power electronics and grid technology are growing. Power electronic converters are central elements in the connection of generators, consumers and storage units, and are playing an increasingly important role for grid control. In order to operate the future energy system flexibly and reliably, they must be designed for increasingly complex requirements. Taking this into account, a new laboratory site at Fraunhofer ISE is being established, in which research, development and testing can be carried out with regard to grid integration and the control of low-, medium- and high-voltage grids by inverters. A substantial part of the sophisticated infrastructure has already been installed. Complete commissioning is planned for the middle of 2018.

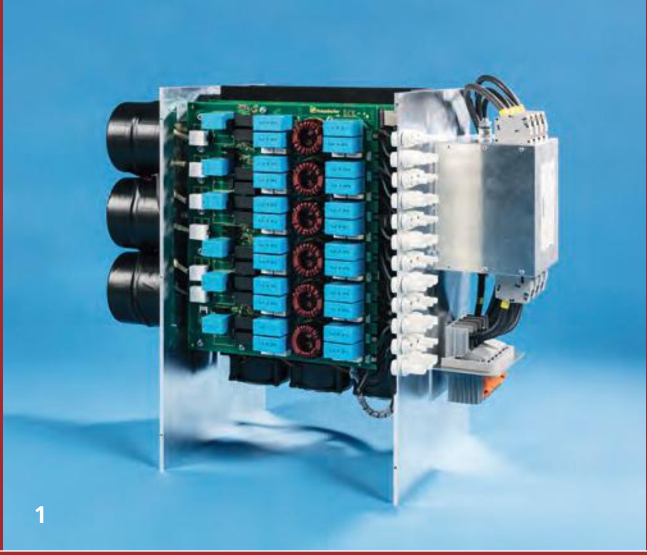
The activities of Fraunhofer ISE in the field of power electronics and grid technology have grown with the challenges of the energy transformation. For many years already, all types of inverters and transformers with a power of up to one megawatt have been tested in our accredited TestLab Power Electronics. We investigate the equipment there with respect to its efficiency value or compliance with grid connection conditions. With construction of the new laboratory, Fraunhofer ISE is taking a further step and will offer its services in future also for equipment and components in the multi-megawatt range and for medium-voltage applications. In addition, research and development activities play an equally important role. We are concentrating particularly on the development of power electronics for:

- Novel, large scale PV power plants
- Land-based and off-shore wind energy systems
- Centralized and distributed energy storage systems
- Sustainable AC and DC grids
- Micro-grid applications
- Charging infrastructure for electromobility
- Mobile applications such as trains, ships and aeroplanes

In addition, we are working on new control algorithms. The focus is on the dynamics and resilience of energy converters, in particular. Concrete problems include e. g. the interactions between inverters operating in parallel, the simultaneous control of different grid levels, error management in complex grid structures and the control of autonomous grid cells or off-grid systems. Another central task will be the integration of power electronics into an increasingly digital world.

In order that developments can be advanced in parallel, several switching stations, test stands and test arrays are being constructed in the medium- and low-voltage range. The new laboratory site will thus be unique in its purpose and its equipment. The project is supported by the German Federal Ministries for Economic Affairs and Energy (BMWi) and for Education and Research (BMBF) with a total amount of around 10 million euros; Fraunhofer ISE is investing a further 5 million euros.

1 *Already installed 110 kV / 20 kV / 40 MVA transformer to connect the multi-megawatt system to the high-voltage grid.*
1 *Model of the future "Center for Power Electronics and Sustainable Grids" in the Zinkmattenstrasse, Freiburg: Main building (left) and laboratory (right).*



Assembly and Cooling Technology

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In order to withstand the continuously increasing cost pressure of a globalized PV economy, new research approaches are needed. Within power electronic circuits such as in PV inverters, the assembly and cooling technology is a central factor for cost optimization. Mechanical and electromechanical components of power electronics represent a material cost share of up to 70 % in commercially available converters.

In order to reduce this share significantly, new assembly concepts and cooling technology are required, which primarily save resources but do not compromise efficiency and reliability. For example, support structures and housings can be developed of robust and, in some cases, conductive compound materials with 3D printing methods. By additionally decoupling the housing and heat sink from each other, different temperature levels can be achieved within the device.

Implementation with different temperature zones allows less expensive components with lower maximum operating temperature to be used. This helps to raise the temperature of the heat sink for better exploitation of the power electronic semiconductor.

In our research work, we have succeeded in increasing the power per weight down by 30 % in comparison to commercial converters and thus to save resources.

1 *Technology demonstrator of a 70 kVA PV inverter with optimized assembly and cooling technology.*

Inverters in the Electricity Grid

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Stable operation of electricity grids depends increasingly on the installed inverters and their interaction with the grid. Already today, grid-feeding inverters with a power of about 80 GW are installed in Germany in wind turbines and PV systems. High-voltage DC transmission stations, battery storage units, electric vehicles, electrolysers and heat pumps are also connected to the electricity grid via power electronics. By 2050, inverter power of more than 500 GW is expected to be installed in Germany. The demands on the equipment are thus increasing in several respects.

In order to compensate for the grid-forming properties of the replaced conventional power plants, future inverters will have to feature a grid-maintaining, rather than a grid-feeding, operation mode. With this goal, Fraunhofer ISE is developing and testing new control algorithms for inverters in the research projects "Zukunftskraftwerk PV" and "Verbundnetzstabil" funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Grids with a large share of inverters, e. g. in large PV systems, tend to create undesirable oscillations, which can disturb operation or even destroy systems. Fraunhofer ISE is investigating this type of voltage problem in the field and in the laboratory, and is developing new characterization procedures to evaluate the stability of inverters in the grid. The goal is to avoid instability reliably by measures within the PV systems or by optimizing the inverter control.

2 *Measurement of upper harmonic currents in a medium-voltage transformer in a PV power plant.*

Digital Methods and Tools for Future Buildings and Grids

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Advancing digitization is creating new opportunities to increase the energy efficiency of buildings and the flexibility of electricity grids. By electronic acquisition of data from building operation and their automated analysis, building operators can gain new knowledge that allows them to make use of previously inaccessible energy-saving potentials. For example, problems in building operation can be detected early and automatically with modern diagnostic procedures, and solved before deficits in comfort or energy losses result. In this process, Fraunhofer ISE is using the method "Building Information Modelling (BIM)" for optimizing the operation of buildings. By providing contextual information from BIM to facility managers maintenance tasks are facilitated.

Predominantly distributed and fluctuating electricity generation changes grid operation fundamentally, as control of the demand side then becomes increasingly important. Modern information and communications technology (ICT) allows distributed generators, building automation and electricity grid operation to be linked. Exploitation of flexibility offered on the consumer side is the foundation of various new business models.

The expertise of Fraunhofer ISE on ICT for buildings and energy systems ranges from monitoring, through the development of automated analytical procedures and reliable and interoperable communication protocols as well as model-predictive control algorithms, through the application of BIM, up to market integration.

1 *Chiller with autonomous measurement and control technology.*

Grid-Supportive Operation of CHP Systems

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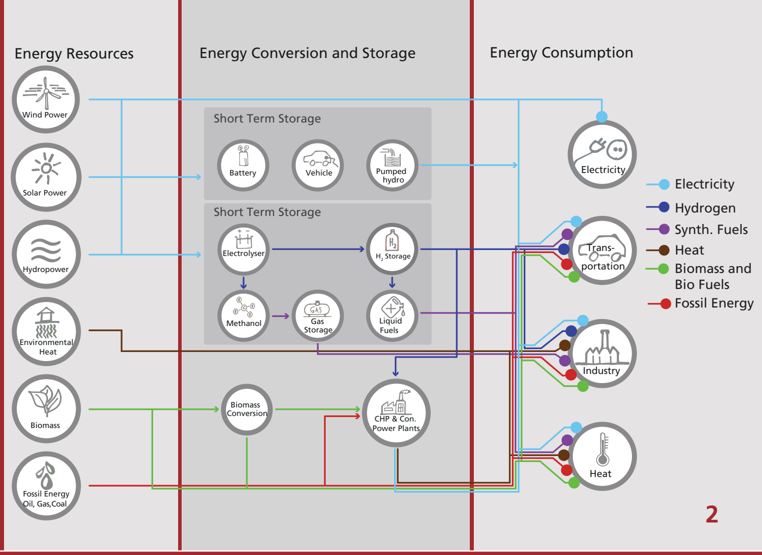
Due to the extensive installation of PV systems, electricity grids are reaching their capacity limits increasingly often, resulting in over-voltages. Installing additional, electricity-generating, combined heat and power (CHP) plants is thus often no longer possible without additional, expensive extension of the grid. Inter-sectoral energy management, in which electricity from the grid is used to generate heat, is often the more appropriate solution.

The grid-supporting controller of Fraunhofer ISE calculates the grid state from a local voltage measurement and determines the suitable voltage input for the heating system. The goal is to stabilize the grid voltage, so if it is low, the CHP system is activated to provide heat, whereas the electric heating is activated if is high. The parameterization of the grid-supportive controller is based on the already known rated power of the locally installed thermal units. The specific sensitivity of the grid connection point is determined automatically by detecting the grid impedance in operation, and is also used for parameterizing the control.

The application was tested in the "Center for Power Electronics and Sustainable Grids" of Fraunhofer ISE with Hardware-in-the-Loop tests. In doing so, it became clear that the statutory voltage limits in the electricity grid can be met, also without extending the grid further. The potential for this type of operation control system is very large. Highly efficient local energy supply with distributed generators and high-quality voltage thus becomes feasible in existing low-voltage grids.

2 *"Hardware-in-the-Loop" simulations.*



Calculation of Sustainable Local Energy Systems with "KomMod"

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More and more local councils and owners of large buildings are pursuing the long-term goal of implementing a climate-neutral energy supply. They need support to determine the optimal energy system structure to achieve this. Fraunhofer ISE has developed the "Kommunales Energiesystem-modell KomMod" (municipal energy system model), with which local energy systems can be optimized with fine time resolution and taking interactions between different sectors into account.

"KomMod" has been applied for 15 projects to date in Germany, the EU and Asia. For example, we calculated that 45 % of the electricity demand for the city of Kaiserslautern could be generated locally from renewable sources, whereby photovoltaics dominated with 33 %. Heat would be generated from thermal solar energy (11 %), biomass (13 %) and electricity (76 %). A 250 MWh electrical storage would buffer the peaks.

For Stuttgart Airport, the amount of renewable energy was determined so that it can contribute toward achieving the climate-protection goals of the State of Baden-Württemberg until 2050. PV would be the dominant local energy source and meet 37 % of the electricity demand, including the demand for electric vehicles used by the aeroplane passengers. For the Chinese industrial city of Xiuzhou/Jiaxing, Fraunhofer ISE has calculated that 33 % of the local energy demand in 2030 could be covered. On commission to Toyota, the type of energy system was determined with which the enterprise's goal of CO_2-neutral car production in its eight European factories can be reached.

1 *For the City of Kaiserslautern, a route was calculated which it can take to achieve a climate-neutral power supply. © Kaiserslautern*

Data and Models for Energy System Analysis

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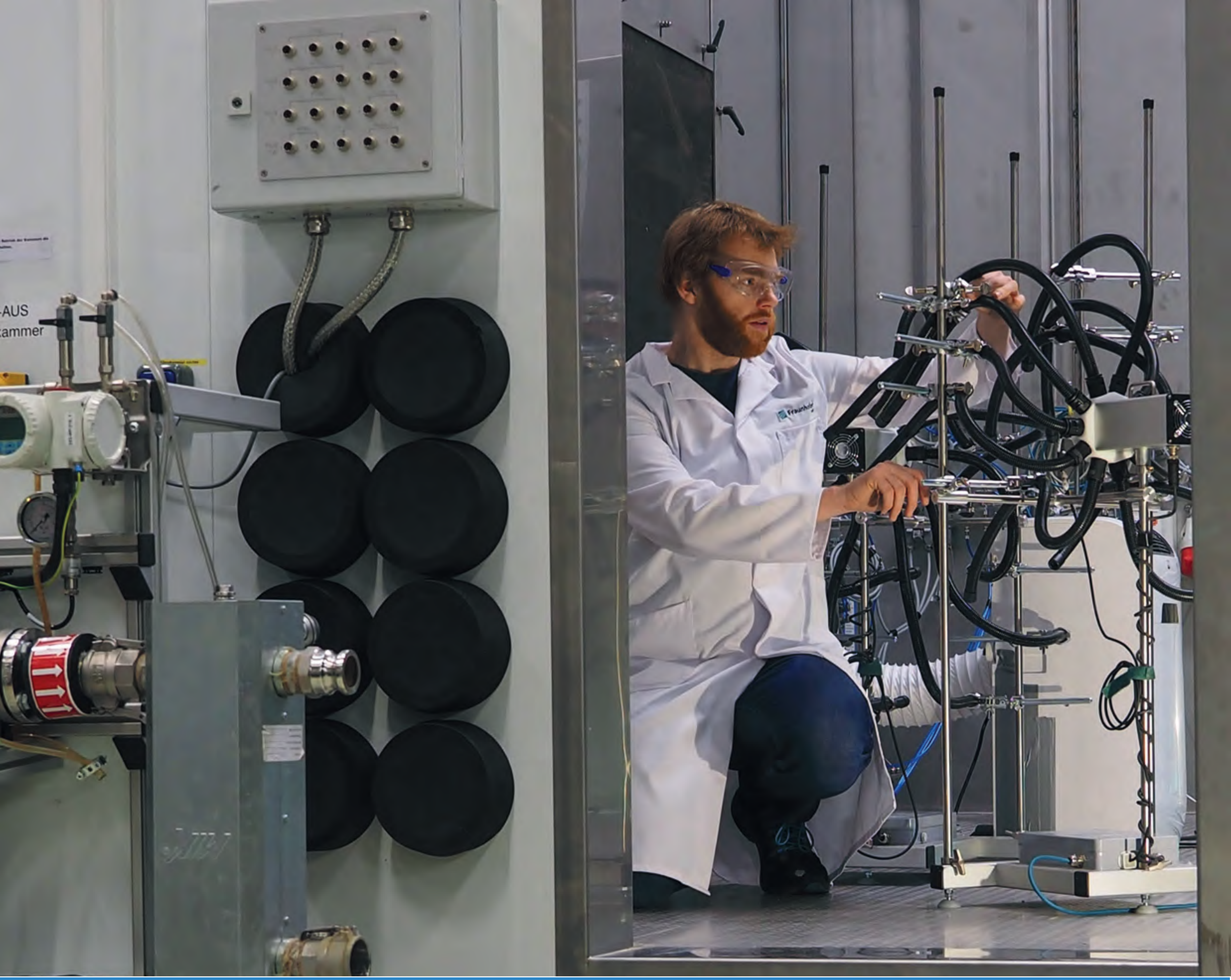
Many enterprises, both in Germany and throughout the world, are concerned with questions such as:

- Where are optimal sites located for power plants based on renewable energy sources?
- How can these power plants be integrated optimally into the energy system?
- Which conventional power plants should still be operated?
- Is the existing power capacity sufficient to guarantee a reliable power supply?
- How expensive are energy technologies allowed to be (e. g. heat pumps, electric vehicles), to be commercially successful?
- How much does it cost to reconfigure an energy supply system?

Fraunhofer ISE is working intensively on methods and tools to answer such questions. Based on a detailed model of all consumption sectors in the inter-sectoral energy system model, "REMod-D", and integrated optimization of power plant capacities, electricity transmission lines and specific regional features in "ENTIGRIS", we can answer our clients' questions comprehensively and specifically. In addition, we possess a comprehensive data bank on energy technology and regulations in Germany and many other countries in Europe and throughout the world. Projects have been carried out successfully both in Germany and internationally, e. g. on questions concerning sites for power plants based on renewables, and technological manufacturers have received advice on strategic decisions concerning their technological portfolios.

2 *Key factors and technologies in an energy system based on renewables in 2050. (Photo source: Cooperation with BMW AG)*



ACCREDITED LABORATORIES

Complementing its research and development activities, Fraunhofer ISE offers various testing and certification procedures to commercial enterprises and research institutes. At present, the Institute has two calibration and five test laboratories which are accredited:

- CalLab PV Cells
- CalLab PV Modules
- TestLab PV Modules
- TestLab Solar Façades
- TestLab Solar Thermal Systems
- TestLab Power Electronics
- TestLab Heat Pumps and Chillers

Since February 2018 our new TestLab Heat Pumps and Chillers has been accredited. It offers the most recent technology to measure and characterize heat pumps and chillers and their components.

i *Measurement of heat pumps and chillers in the calorimetric climatic chamber of Fraunhofer ISE.*

Calibration of Solar Cells

cells@callab.de

CalLab
PV Cells

CalLab PV Cells at Fraunhofer ISE offers the calibration and measurement of solar cells from a wide range of PV technologies 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 as a 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 improving uncertainties and developing new measurement procedures. For example, the change in solar cell parameters with different angles of incidence plays an important role for the yield in practical applications. A new procedure, which allows us to determine the spectrally resolved angular dependence, was introduced in 2017. Furthermore, new measurement procedures and measurement facilities for faster or more accurate determination of the spectral response were developed.

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, new material combinations for the absorber, as in perovskite solar cells, and the measurement of bifacial cells are important aspects addressed by our new developments. Various multiple-source simulators allow us to make measurements under almost any standard conditions, such as are needed for space and concentrator applications. Using our spectrally adjustable flash lamp based sun simulator, multi-junction solar cells with up to four pn junctions can be measured under concentrated irradiance 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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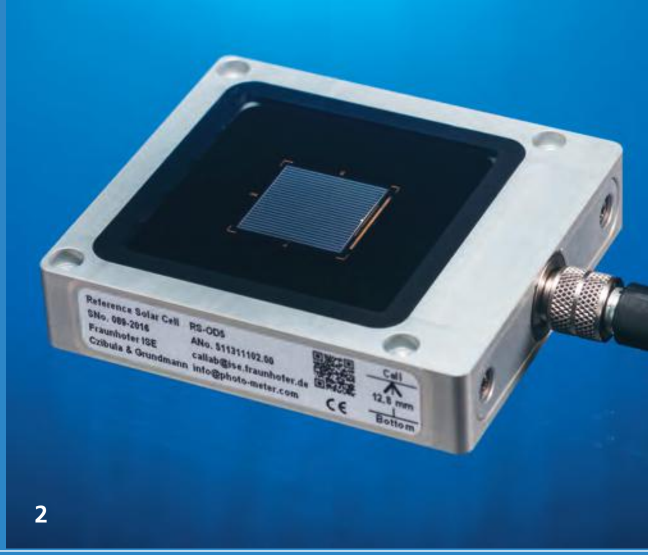
Standards and Specifications

» Accreditation as a calibration laboratory according to DIN EN ISO / IEC 17025
» AM 1.5g (IEC 60904-3)
» AM 0 (ISO 15387)
» AM 1.5d (ASTM G173-03)

1 *Steady-state solar simulator in CalLab PV Cells.*



Calibration of PV Modules

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CalLab
PV Modules

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The accredited calibration laboratory has achieved a new best benchmark: Photovoltaic modules can now be calibrated with a measurement uncertainty of only 1.3 %. The measurement accuracy was confirmed by the Deutsche Akkreditierungsstelle (DAkkS). The most recent inter-laboratory comparison with NREL, AIST and JRC showed deviations of less than 0.9 % for the power values of crystalline modules. On the basis of our internationally leading measurement accuracy, we offer support from the accurate calibration of individual cells and modules up to complex, client-specific tasks, e. g. to calibrate bifacial modules.

The high measurement accuracy is decisive for module manufacturers, above all. With more accurate reference modules, the measurement uncertainty in module production can be reduced and the performance characteristics in data sheets can be stated with smaller tolerance values. We also offer accurately calibrated reference cells from our own developments for different applications.

As part of our quality benchmarking, we apply individual testing procedures to support both the selection of module suppliers for large PV projects and also quality assurance during procurement of large batches of modules. Analysis of modules sampled randomly in the field now provides operators and investors of PV power plants with yet more accurate information about the real performance of their modules. In cases of damage, our independent measurements can also help to determine deviations from guaranteed power more accurately.

For accurate long-term characterization of PV modules, we offer a module monitoring system from our own developments for operation at the client's site. The measurement system includes highly resolved DC measurement data (IV characteristics) of individual modules. This allows comprehensive characterization of modules in operation with respect to their yield properties, particularly for new technologies such as bifacial modules.

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.

Standards and Specifications

- Accreditation as a calibration laboratory according to DIN EN ISO / IEC 17025
- Calibration of PV modules with a measurement uncertainty of only 1.3 %
- Determination of the spectral response at the module and cell level from 300 nm to 1200 nm
- Precision measurement according to IEC 60904-3 with a measurement uncertainty of only 1.5 %
- Power Rating measurements according to IEC 61853
- Evaluation of CPV modules under CSOC and CSTC
- IEC 62670-3 for CPV modules

1 *Bifacial PV module.*

2 *Reference cell for outdoor application.*

Quality Assurance of PV Modules

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TestLab
PV Modules

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

We advise our clients in the definition of cost-effective and efficient testing programmes as well as on individual quality criteria. The tests 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.

We apply innovative and recently developed analytical methods to systematically investigate defects such as so-called snail trails, Potential Induced Degradation (PID) and Light and elevated Temperature Induced Degradation (LeTID). TestLab PV Modules offers specific tests and test sequences for many typical defects.

Our platforms provide extremely accurate measurement values and precisely reproducible testing procedures for comprehensive characterization. Very accurate power measurements are carried out in our accredited calibration laboratory, CalLab PV Modules, with an internationally leading measurement uncertainty of only 1.3 %.

In close cooperation with our partner, the VDE Prüf- und Zertifizierungs-institut, we certify modules according to international quality and safety standards. Furthermore, we have developed the “VDE Quality Tested” certificate, which enables continuous quality control of module production from an independent body at a high level.

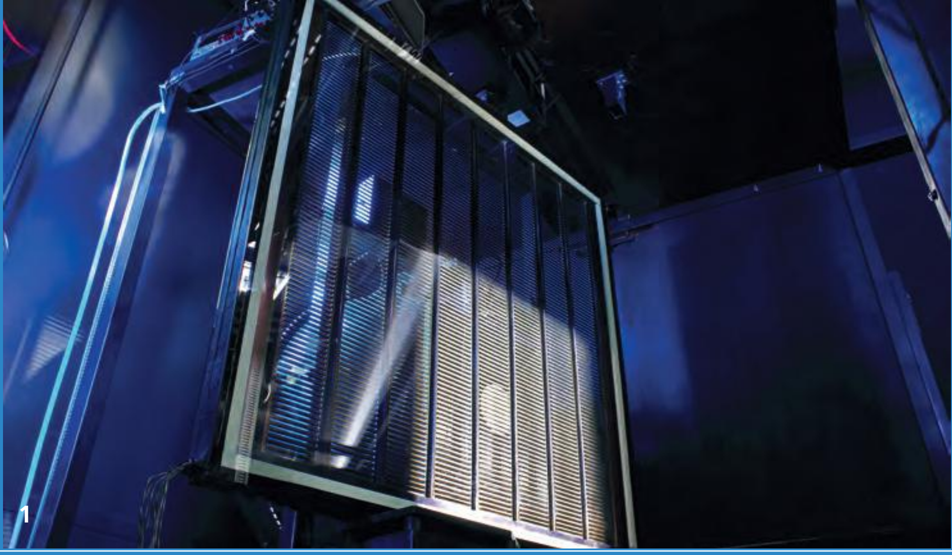
We offer model-based, long-term stability tests, which take account of the specific climatic challenges in deserts or at tropical locations, to determine the suitability of modules for application in these regions.

Daniel Philipp
Phone +49 761 4588-5414

Standards and Specifications

- » Accreditation according to DIN EN ISO / IEC 17025
- » IEC 61215-1:2016 Terrestrial PV Modules – Design qualification and type approval - Part 1: Test requirements
- » IEC 61215-2:2016 Part 2: Test procedures
- » UL 1703 Standard for Flat-Plat PV Modules and Panels
- » IEC 61730-1:2016 PV module safety qualification (Part 1: Requirements for construction)
- » IEC 61730-2:2016 (Part 2: Requirements for testing)
- » IEC 61701:2011 Salt mist corrosion testing
- » IEC TS 62804-1:2015 PV Modules – Test methods for the detection of potential-induced degradation (PID)
- » Sand abrasion test

1 *The safety, reliability and quality of PV modules are tested in TestLab PV Modules.*



Characterization of Façades and Building Components

testlab-solarfacades@ise.fraunhofer.de

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.

The laboratory is accredited 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, such as 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).

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.

BSDF data sets (bi-directional scattering distribution function) are determined goniometrically and are 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.

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

g value and U value testing
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Standards and Specifications

- Accreditation according to DIN EN ISO / IEC 17025
- Transmittance, reflectance and g value according to DIN EN 410, ISO 9050, DIN EN 13363, DIN EN 14500, DIN EN 14501
- Thermal conductivity and U value according to ISO 8302, DIN EN 673, DIN EN 674
- Solar Reflectance Index (SRI) according to ASTM E1980

Testing of Collectors, Storage Tanks and Systems

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TestLab
Solar Thermal
Systems

The high quality and expertise of TestLab Solar Thermal Systems was confirmed again in 2017 by by extension of its accreditation by the Deutsche Akkreditierungsstelle (DAkkS). With this accredited status, we facilitate our clients' access to the market, also internationally. The portfolio covers all types of solar collectors and thermal storage units as well as complete systems. We also apply our test methods to support our clients with innovative approaches, e. g. in the development of solar thermal heating 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, also well beyond the limit of methods prescribed by standards. Together with TestLab PV Modules at Fraunhofer ISE, which is also accredited, we offer measurements for complete certification of PVT collectors (IEC and ISO). We are equipped with an accredited solar air-heating collector test stand.

Other types of products can be measured 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. Also, systems drawing on several sources, such as the combination of PVT collectors with a heat pump, can be tested here as a complete installation. Our indoor test stand with a 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 for widespread collector certification have been created at TestLab Solar Thermal Systems. Our testing is fundamentally based on the updated version of EN ISO 9806:2017. We are actively accompanying the new revision of the collector testing standard. This can be offered directly for all types of collector technology included in its scope and for all modifications to the testing methods within the scope of our accreditation.

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Collectors
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Storage tanks, systems
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Standards and Specifications

- Accreditation according to DIN EN ISO / IEC 17025
- EN ISO 9806
- EN 12975
- EN 12976-1,2
- EN 12977-1,2,3,4,5
- Solar Keymark
- CE
- SRCC

1 *Collector in the hail test stand.*

Characterization of Power Electronic Equipment

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TestLab
Power Electronics

Roland Singer
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In the accredited TestLab Power Electronics, we characterize power electronic equipment with a power rating into the megawatt range. DC sources with a total power output of 1.4 MW are available for this purpose. They can be flexibly parameterized and simulate e. g. the behavior of PV generators. Highly accurate measurement instruments with a broad dynamic range serve to characterize the test objects. To operate grid-connected power converters with a power rating of up to 1.25 MVA, voltages can be applied flexibly in the laboratory over a wide range from 255 to 790 V. We can simulate grid faults in the medium-voltage grid in order to investigate dynamic grid support by power generators (Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT)). Further analyses are carried out with a 600 kW grid simulator.

Outside our laboratories, we offer our clients field measurements, for instance in 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 outdoor test field, a flexibly configurable PV generator with a rated power of 1 MWp is available, which can be used for testing inverters under real system conditions. Grid connections are possible on both the low-voltage and the medium-voltage side. Other larger generator units (e. g. combined heat and power plants) can be tested with a 4.5 MVA LVRT test container.

We measure power-generating units according to international grid codes, e. g. for Germany, China or Great Britain, characterize battery converters with our own specially developed testing methods and determine the efficiency of power electronic equipment with high accuracy. We support our clients in modelling power-generating units, PV power stations or grid segments. When planning and conducting measurement campaigns, we always react flexibly to the requirements of our clients and offer detailed advice and support, also in the preliminary phases.

1 *Laboratories of the TestLab Power Electronics.*

Standards and Specifications

» Accreditation according to DIN EN ISO / IEC 17025
» FGW TR3 Revision 23 / 24: Determination of the electrical properties of generator systems in the medium-voltage, high-voltage and highest-voltage grid
» FGW TR4 Revision 7 / 8: Specifications for modelling and validating simulation models of the electrical properties of generator units and systems
» DIN EN 61400-21: Measurement and assessment of power quality characteristics of grid-connected wind turbines
» DIN EN 61683: Photovoltaic systems – Power conditioners – Procedure for measuring efficiency
» DIN EN 50530: Overall efficiency of grid-connected photovoltaic inverters
» TLPE-HV-001: Determination of the conversion efficiency of bidirectional converters based on DIN EN 50530
» LPE-HV-002: Determination of the effective and reactive power behavior of bidirectional converters based on the TR3
» TLPE-HV-003: Determination of the frequency-reactive power behavior of bidirectional converters based on the TR3

Measurement and Testing of Heat Pumps

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TestLab Heat Pumps and Chillers offers state-of-the-art technology for developing, measuring and characterizing heat pumps and chillers, as well as their components. The modular test rig concept makes it possible 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 electrically driven systems with a connection power of up to 30 kW, thermally driven equipment – heat, natural gas or a test gas – can also be measured. The laboratory is equipped with an integrated safety concept which allows components and systems with flammable refrigerants or ammonia to be set up and measured.

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, brine and air, which can provide the relevant 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 m^3/h to 5000 m^3/h) can be conditioned in the temperature range from -15 °C to 50 °C and relative air humidity from 15 % to 95 %.

Systems can be measured in our laboratory according to all common standards and technical codes. The test lab has been accredited according to DIN EN ISO / IEC 17025 since February 2018. Beyond standardized methods, we cooperate with our clients to develop individual measurement procedures, which enable efficient and cost-effective development and optimization of devices and more complex systems by realistic, dynamic measurement sequences, including hardware in the loop. We also design and operate component-specific test stands (e. g. compressor test stand, diverse heat exchanger test stands), where advanced measurement and analytical technology from fluid mechanics, acoustics, vibrations and gas analysis is used to address specific questions (e. g. particle image velocimetry (PIV), Laser Doppler Anemometry (LDA), shadowgraphy, gas chromatography, scanning vibrometry).

TestLab
Heat Pumps
and Chillers

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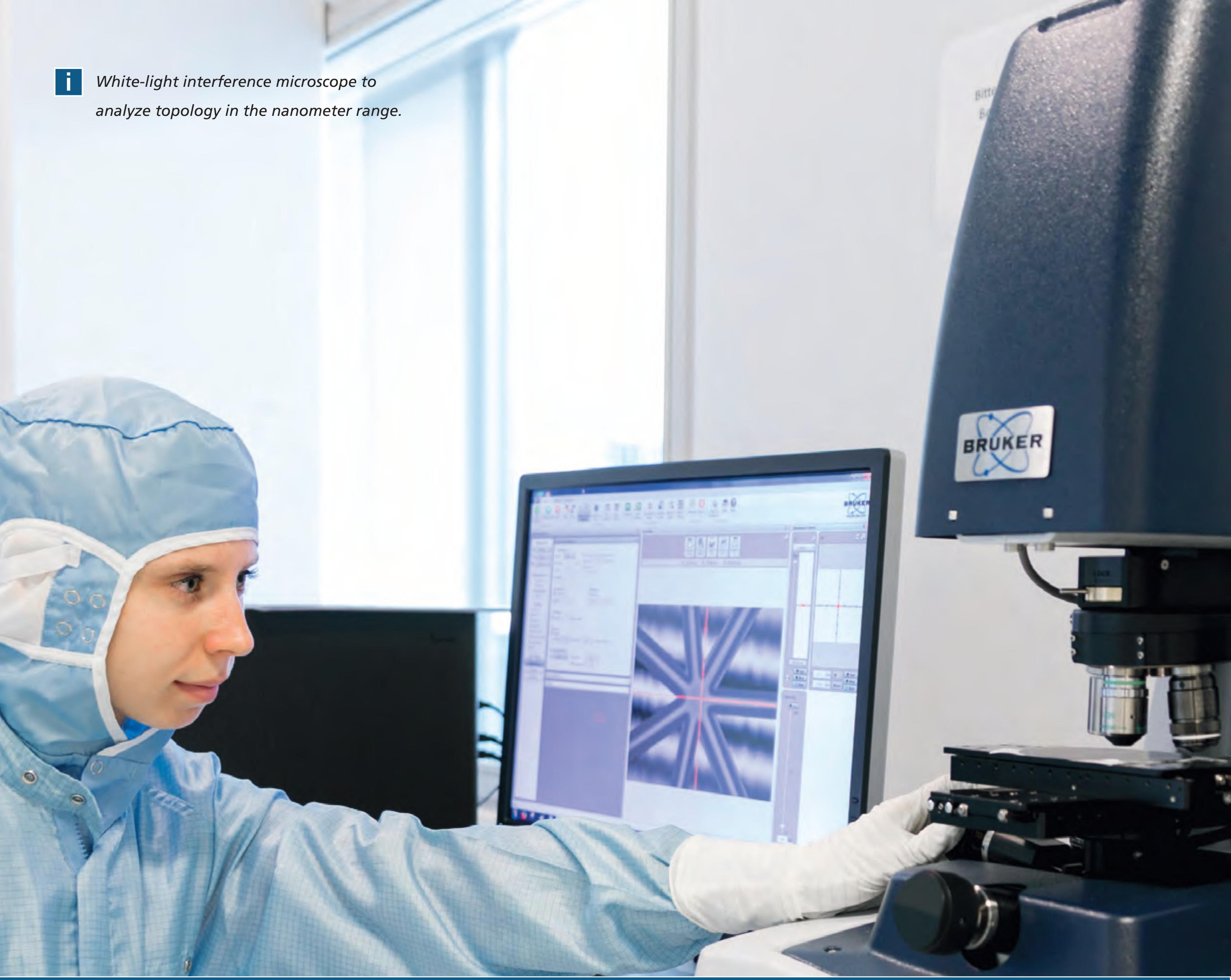
Cell phone +49 162 205 3924

Standards and Specifications

- » Accreditation according to DIN EN ISO / IEC 17025
- » Testing standards EN 14511, EN 14825, EN 16147, EN 12309
- » All tests for Energy Labelling of heat pumps and chillers according to the Ecodesign guideline
- » Heat Pump Keymark
- » EHPA Quality Label
- » Staff certified according to the F gas regulation, Class I

1 *Heat pump test stand at the TestLab Heat Pumps and Chillers at Fraunhofer ISE.*



White-light interference microscope to analyze topology in the nanometer range.

R&D INFRASTRUCTURE

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of 15 000 m² and state-of-the-art equipment and modern facilities are the basis for our competence in research and development. Clean-room laboratories with a floor area of 500 m² are included. The R&D infrastructure of Fraunhofer ISE is divided into eight Laboratory Centers and four production-relevant Technological Evaluation Centers:

» Center for High Efficiency Solar Cells
» Center for Emerging PV Technologies
» Center for Heating and Cooling Technologies
» Center for Energy Storage Technologies and Systems
» Center for Material Characterization and Durability Analysis
» Center for Power Electronics and Sustainable Grids
» Center for Optics and Surface Science
» Center for Fuel Cells, Electrolysis and Synthetic Fuels
» SiM-TEC – Silicon Materials Technology Evaluation Center
» PV-TEC – Photovoltaic Technology Evaluation Center
» Module-TEC – Module Technology Evaluation Center
» Con-TEC – Concentrator Technology Evaluation Center

The technical infrastructure is continually developed further, so that the Institute can always carry out research and development projects for its clients according to the most recent state-of-the-art. In 2017, the foundation stone was laid for a new Center for High Efficiency Solar Cells, in which further innovations for solar cell technology should be developed from 2020 onward. Eight of the technological Centers for development or production-relevant testing are presented in more detail on the following pages.

1

Center for High Efficiency Solar Cells

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In the "Center for High Efficiency Solar Cells", we evaluate technologies with which highest PV efficiency values can be achieved, and implement them at the uppermost international level. Applications for high efficiency solar cells include not only conventional solar modules but also power supplies for satellites, electric vehicles, autonomous sensors and electronic devices. Fraunhofer ISE holds several world records in the high efficiency solar cell sector, such as the record efficiency value for multicrystalline silicon (22.3 %), but also the absolute efficiency record of 46.1 %, based on a III-V multi-junction cell architecture.

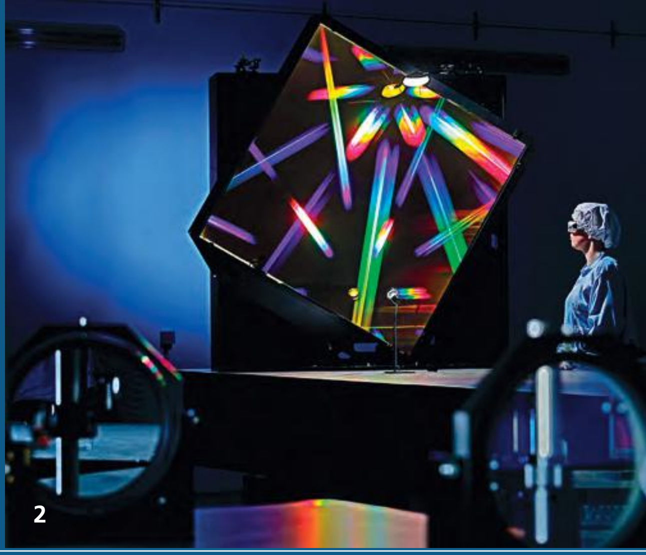
In order to advance this top position still further, we laid the foundation stone for a new laboratory building in 2017, which will contain clean-room laboratories with equipment suitable for meeting future technological challenges. In the new "Center for High Efficiency Solar Cells", advanced PV technology can be tested and optimized in state-of-the-art laboratories with a floor area exceeding 1000 m^2. Research will be conducted there on innovative processes and technology for future application in industry. In addition to further development of silicon and III-V technology, one focus of the new center is on the combination of these two materials: High efficiency silicon-based tandem cells represent one of the most promising photovoltaic technologies. With the new laboratory, Fraunhofer ISE intends to develop path-breaking new solar cell types and technology also in the future, and to contribute to making the German photovoltaic industry internationally competitive.

1 *Visualization of the "Center for High Efficiency Solar Cells" on the campus of Fraunhofer ISE in Freiburg. The foundation stone of the new building was laid in October 2017. © BW+P Architekten*

Technical Facilities

- Flexibly usable clean-room laboratory in future with 740 m²
- Further laboratory areas of 340 m^2
- High-temperature diffusion (BBr_3, $POCl_3$)
- High-temperature oxidation (dry and moist)
- Ion implantation (P, B, H, Ga, Si)
- Wet-chemical processes for purification and structuring
- Yellow-light zone for photolithography and laser lithography to create microstructures with bifacial alignment
- Wafer-bonding technology
- Plasma technology (PECVD and etching)
- Atomic layer deposition (ALD)
- Processing of wafer dimensions up to 157 x 157 mm^2
- Thermal and electron-beam evaporation of metals and dielectric layers
- Galvanic metallization
- Extensive instrumentation for characterizing materials and components

1



2

Center for Optics and Surface Science

Dr Thomas Kroyer | Phone +49 761 4588-5968 | Dr Benedikt Bläsi | Phone +49 761 4588-5995

In the "Center for Optics and Surface Science", we develop optically functional surfaces for numerous applications, using large-area coating and structuring processes.

We apply our coating technology, based on sputtering, to find solutions in the fields of solar thermal energy, photovoltaics, energy-efficient buildings, thin-film batteries and hydrogen technology. The applications include reflectors and absorbers for solar thermal power plants, transparent electrodes and colored cover panes for photovoltaics, low-emissivity and solar-control coatings as well as optically switchable systems for energy-efficient buildings. In addition to optimizing the optical properties, we tailor thin-film stacks to meet the relevant specifications for the final product, e. g. long-term stability in outdoor applications or scalability to industrial production scales. Furthermore, we offer support with system integration of functional stacks of layers, e. g. in a module or a façade. Our spectrum of services comprises feasibility studies, hatch testing and product developments up to complete industrial prototypes.

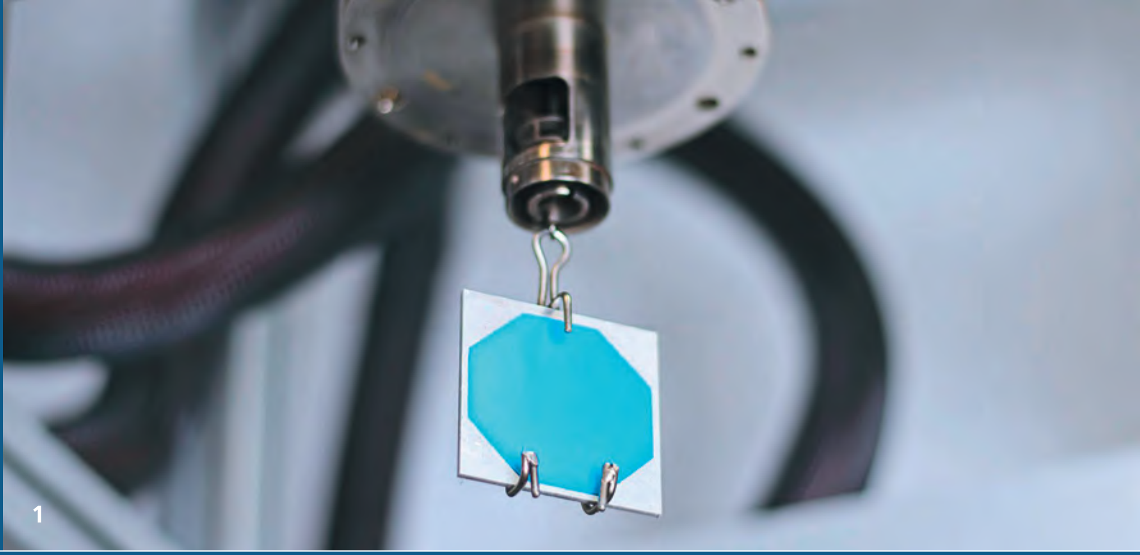
Structuring surfaces on a micrometer to nanometer scale enables a great variety of optical and non-optical functionality to be achieved. The large-area production of such surface structures in customized forms and dimensions is the basis for industrial implementation. In solar cells, photonic structures result in more efficient light trapping and improved utilization of the solar radiation. In lighting applications, microstructures and nanostructures are used to couple light out of LEDs or direct it into desired directions. In displays, functional structures are used for anti-reflective surfaces, polarization-dependent optical applications or light redirection. Microstructures and nanostructures also play a role in modifying non-optical properties, e. g. by influencing the wettability, adhesion or friction of surfaces.

1 *Horizontal sputtering equipment, coating area 1.5 x 4 m², equipped with up to 10 planar and double cylinder cathodes as well as a plasma-etching station.*

2 *Interference lithographic equipment to produce seamless microstructures and nanostructures over areas of up to 1.2 x 1.2 m².*

Technical Facilities

- State-of-the-art sputtering equipment with a coating area of up to 1.5 x 4 m² with a maximum height difference (pitch) of 16 cm
- Substrates: flat and curved glass panes, polymer films and metal sheets and pipes
- Interference lithographic equipment to produce master structures with structure details between 100 nm and 100 µm homogeneously over areas of up to 1.2 x 1.2 m²
- Nano-imprinting and hot-embossing equipment to transfer microstructures and nanostructures onto prototypes
- Roll-to-plate nano-imprint tool for production-relevant processes
- Plasma-etching equipment to transfer imprinted structures onto non-polymer materials
- Characterization of the electrical, optical, microstructural and chemical properties of coatings and structures: Fourier spectrometer, film stress measurement, scanning electron microscopy (SEM), atomic force microscopy (AFM), Auger spectrometry, mechanical abrasion tests, electrochemical methods



1

Center for Material Characterization and Durability Analysis

Dr Karl-Anders Weiß | Phone +49 761 4588-5474 | PV-Modules: Daniel Philipp | Phone +49 761 4588-5414
PV Cells: Dr Martin Schubert | Phone: +49 761 4588-5660

In the "Center for Material Characterization and Durability Analysis", Fraunhofer ISE pools its technical competence in the testing and measurement of many different materials for applications in active and passive solar energy utilization, energy storage and building energy technology.

One focus is the comprehensive analysis of the material characteristics. We specialize in the investigation of semiconductors, solar cells, photovoltaic modules, thermochemical and porous materials (e. g. zeolite), phase change materials (PCM), phase change slurries (PCS), polymers as well as coatings on glass and metal and develop suitable, new methods for material characterization, especially non-destructive analytical methods. We also have many years of expertise in investigating material performance under different load conditions e. g. in different climate zones. In order to predict the performance and durability of materials under these different applications, we make use of data from analytical measurements, real operation and from accelerated lifetime tests. We also create simulation models in order to calculate the material behavior and degradation.

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

Technical Facilities

Material Characterization

» Dilatometer
» Differential Scanning Calorimeter DSC (10 µl to 10 ml, -90 to 700 °C)
» Modulated temperature calorimeter (up to 100 ml, -10 to 180 °C)
» Hot plate system (up to 50 cm x 50 cm) to determine the heat capacity as a function of temperature
» Laser flash and hot-wire apparatus to determine the heat and thermal conductivity (-90 °C to 500 °C)
» Lock-in thermography and electroluminescence
» BET porosimetry to determine surface area and pore structure of highly porous materials
» X-ray diffractometer (XRD) to determine crystal structure
» Confocal Raman microscope with AFM
» Rotational rheometer to determine flow behavior of materials in the range from -20 °C to 600 °C
» Mass spectrometer to determine temperature-dependent permeation characteristics of barrier materials
» FT IR spectrometer with integrating spheres (UV/visible, IR)
» Photoluminescence, thermographic and electrical methods for the spatially resolved and quantitative analysis of silicon material quality and solar cells

Durability Analysis

» Outdoor test sites with comprehensive monitoring in different climate zones
» Cyclic temperature tests of PCM and hydrothermal cycling of adsorbent composite samples
» Test set-ups for investigation degradation of materials and components, for semiconductors, solar cells and modules

Center for Energy Storage Technologies and Systems

Dr Matthias Vetter | Phone +49 761 4588-5600 | Dr Daniel Biro | Phone +49 761 4588-5246

In the "Center for Energy Storage Technologies and Systems", Fraunhofer ISE is focussing particularly on battery technology. We are working with novel materials and developing innovative production processes for battery cells and pursue new approaches for battery systems technology – from the cell, through the module, up to the complete battery pack including battery and thermal management. We optimize procedures to determine the state of charge and state of health as well as to predict the lifetime. In addition, we work on optimized charging and operation management strategies as well as battery system prototypes for widely varying application areas.

Our activities also include the modelling and simulation of batteries. We work with electrical, electrochemical and thermal models at the materials, on cell and system level. We carry out comprehensive testing and checking of batteries, including performance and aging investigations (calendaric, cyclic), thermal investigations, abuse tests and post mortem analyses. Furthermore, we have the competence to test different PV storage systems such as pico PV systems, Solar Home Systems, PV hybrid systems, grid-connected PV battery systems and storage system components (charge controllers, energy management systems, etc.).

We specialize in the comprehensive quality assurance of electrical and thermal storage systems. Our methods range from simulation-based system layout and optimization, through system tests in the laboratory and in the field up to system monitoring. In the area of thermal storage this includes both heat and cold storage.

1 *Research and test center for battery technology.*

Technical Facilities

- Basic processing chain for the production and processing of materials for battery cells
- Test circuits for cycling small battery cells and measurement systems for electrochemical characterization of new battery chemistries
- Battery test circuits up to system level with 250 kW (1000 V, 600 A)
- Climatic chambers with safety equipment
- Isothermal battery calorimeter
- High-accuracy coulombmetric test stand
- Test rigs for complete PV home storage systems up to 15 kW (Hardware-in-the-loop)
- Test facilities for DC applications, e. g. for lamps
- Electronics laboratory for the development of battery management systems and electronics for small PV systems
- Off-Grid Laboratory: Testing and measurements for the characterization and certification of small PV battery systems (pico PV systems and Solar Home System kits), components (e. g. charge controllers) and DC-powered products
- PV battery-diesel system test stand
- Test stands to characterize thermal storage units in the temperature range from -30 °C to 550 °C
- Monitoring system for energy relevant analysis of thermal storage units in application
- Test facility to characterize storage systems according to EN 12977-3

Center for Fuel Cells, Electrolysis and Synthetic Fuel

Dr Christopher Hebling | Phone +49 761 4588-5195

In the "Center for Fuel Cells, Electrolysis and Synthetic Fuels", components and sub-systems for hydrogen technology are tested and characterized with scientifically based methods for applications in the fields of PEM electrolysis, PEM fuel cells (particularly for automotive applications), Power-to-Gas (PtG), Power-to-Liquid (PtL) and Power-to-Chemicals (PtC).

1 *Climatic chamber to characterize fuel cell stacks and systems with power of up to 5 kW_{el}.*

Technical Facilities

PEM Electrolysis

- Two test stands to characterize electrolyser stacks (200 kW and 1 MW)
- Hydrogen feed-in system for a natural gas pipeline to investigate PtG technology
- Several single-cell measurement rigs and test stands for short stacks, for fully automatic characterization of PEM electrolyser cells in a wide range of operating conditions
- Hydrogen filling station as a research platform to test new sensors and processes

PEM Fuel Cell Systems

- System for multi-channel impedance spectroscopy for spatially resolved characterization of (automotive) single cells
- Multi-channel impedance spectroscopy for simultaneous single-cell monitoring of (automotive) short stacks
- Fully automated test stand to characterize (automotive) short stacks up to 20 kW / 1000 A with the option to connect peripheral components for system-relevant tests
- Several high-quality, fully automated single-cell test stands for in situ characterization of fuel cell components and single cells
- Walk-in climatic chamber with a temperature range from -40 °C to +80 °C and a humidity range from 5 % to 95 % relative humidity

Synthetic Fuels

- Determination of ignition delay times for liquid and/or gaseous fuels
- Fully automated miniature plant including recycling of unreacted educts to synthesize liquid fuels such as methanol from CO_2-rich input gases and hydrogen

PV-TEC – Photovoltaic Technology Evaluation Center

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The PV-TEC – Photovoltaic Technology Evaluation Center at Fraunhofer ISE was established in 2005 to fill the gap between laboratory research and industrial application. State-of-the-art processing and characterization equipment is available in this large laboratory for the development of silicon solar cells.

PV-TEC focuses on the following core topics in the fields of production and measurement technology for crystalline silicon solar cells:

- Evaluation and development of production processes and processing technology components
- Development and production of advanced industrial solar cell structures
- Characterization and development of materials and solar cells
- Further education and training for PV technology
- Process transfer with on-site support
- Economic cost studies

PV-TEC supports enterprises from all parts of the PV value chain, such as manufacturers of solar cells, modules, processing equipment and materials (silicon and processing materials).

PERC Solar Cells

In PV-TEC at Fraunhofer ISE, we are working on continuous further development and optimization of the standard process to produce silicon solar cells, and extend this with innovative processes such as diffusion and laser processes to create selective emitters or printing processes for fine linear contacts with contact widths of less than 30 µm. This ensures that a high-quality, continually optimized baseline process is available in PV-TEC, which forms the reference for process development. PV-TEC is also able to use partly processed solar cells in all industrially widespread formats and to evaluate selected processes and processing sequences.

The current focus of work is on the PERC solar cell (passivated emitter and rear cell), which enables a significant increase in efficiency and is currently being introduced to the market by numerous companies. A further emphasis is on solar cells with passivated contacts with a potential efficiency value exceeding 25 %, which represent the next developmental step.

1 *Input zone of a large-area, multi-chamber PECVD coater (plasma-enhanced chemical vapor deposition).*

Technical Facilities

PV-TEC front end

- Wet-chemical batch and inline equipment for texturing, purification and single-sided surface processing
- Fully automated tubular furnace facility for diffusion, oxidation and deposition of polycrystalline Si layers
- Fully and partly automated PECVD equipment to deposit dielectric and intrinsic and doped amorphous Si films
- PVD (physical vapor deposition) equipment to deposit layers of metals and transparent conductive oxides (TCO)

PV-TEC back end

- Printing and laser technology processing equipment
- Inline furnaces equipped with very flexible cell testers
- Fully automated screen-printing line including a dispensing unit for fine linear metal contacts on the front surface
- Numerous partly automated printing processing systems: screen-printing, dispensing, ink-jet and rotary printing

1

2

Module-TEC – Module Technology Evaluation Center

Martin Wiese | Phone +49 761 4588-5043

Module-TEC offers extensive facilities to develop module technology. It fills the gap between laboratory development and industrial production technology by allowing relevant charge numbers and formats to be processed. In addition to production and processing technology, numerous analytical facilities are available for quality control. Our research is concentrating on connection technology for crystalline solar cells, integration of high-efficiency cells into modules and the analysis and optimization of module efficiency. In parallel, we are developing application-specific customized modules for building integration (BIPV) and integration into vehicles.

1 *Infrared heating unit for fully automated series connection of high-efficiency crystalline solar cells.*

2 *Semi-automated and fully automated test stands for solar cell interconnection.*

Innovative Adhesive Connections

A state of the art industrial stringer with infrared soldering technology is available for series connection of crystalline solar cells. The equipment is able to produce contacts with three, four or five busbars on solar cells. In addition, half-cells can be connected fully automatically with a high throughput.

In addition to the commercially widespread process for soldered contacts, the stringer offers a gentler, fully automated process for contacting solar cells with electrically conductive adhesives (ECA). This innovative concept of adhesive connection is particularly suitable for temperature-sensitive high-efficiency cells, such as hetero-junction solar cells. A technically sophisticated cell-holding concept combined with IR radiation allows contact-free and mechanically low-stress processing of the cells at industrial throughput rates.

Technical Facilities

- Fully and semi-automated equipment for electrical series connection of cells (IR, contact, induction)
- Back-contact stringer for fully automated connection of cells of different formats with both contact polarities on the back surface of the solar cell (metal wrap-through MWT, inter-digitated back contacts IBC)
- 6-axis robot for automated lay-up of the solar cell strings, production of back-contact modules with conductive back surface films, pick-and-place tasks and controlled UV curing
- 3D X-ray computer tomography
- Two laminators on an industrial scale for encapsulating solar cells, adapted for thicker configurations and spherically curved modules
- Digital microscopy and scanning electron microscopy for the analysis of joints
- Instruments for mechanical characterization of module materials (static and dynamic) as well as for adhesion testing
- Electroluminescence and gel content analysis for quality control of production processes

Con-TEC – Concentrator Technology Evaluation Center

Maike Wiesenfarth M. Sc. | Phone +49 761 4588-5470

Our activities on concentrator module development are merged in Con-TEC. Here, we develop new generations of PV modules with high and low concentration factors, and test components and production processes. Further foci of our research are reliability and materials analysis. We have already demonstrated lens-based FLATCON® modules with efficiencies of up to 36.7 % (CSTC) that were manufactured on semi-automated production equipment. We support companies along the complete value chain for concentrating photovoltaics.

In Con-TEC, we use our production-relevant fabrication processes to produce concentrator modules with the highest efficiency and demonstrate ways to reduce costs. We produce prototypes in small series to evaluate new components, designs and processes. Our possibilities and experience in selecting and processing optical silicone materials are unique; we use silicones to produce optical elements, for optical coupling in secondary optics or to encapsulate solar cells.

Regarding the investigation of the reliability of assemblies, in concentrating photovoltaics, particularly the thermal interconnection of the solar cell to the substrate is decisive. This is because the concentrated irradiation means that very large energy fluxes have to be transferred. Accelerated aging tests are carried out to investigate the long-term stability of the modules or components.

1 *Alignment and assembly equipment for accurate alignment of the base plate and the lens plate of a concentrator module.*

Technical Facilities

- Highly accurate pick & place of solar cells and components on small and large areas (small: < 250 x 300 mm² with a positioning accuracy of 25 µm @ 3 sigma and large: < 600 x 1170 mm² with 75 µm @ 3 sigma)
- Soldering under air or nitrogen atmosphere, controlled curing of conductive adhesives
- Vacuum soldering of areas of up to 300 x 300 mm² with void-free interconnection
- Soldering without flux by applying formic acid or activation with forming gas
- Bonder for heavy and thin gold and aluminium wires
- Equipment to align primary optics to the solar cell
- Dispensing units to apply adhesives and viscous mounting materials
- Coordinate measurement equipment (MarVision OMS 1000 / 350) with a large measurement area (800 x 1050 mm²) and extremely high measurement accuracy (resolution of 0.1 µm)
- Pull and shear tester (Dage Series 4000)
- Climatic chambers for temperature treatment or thermal cycling, with or without additional loads due to elevated air humidity; testing of solar cell components with applied reverse voltage and irradiation of optical components or encapsulation materials with concentrated UV radiation

EDITORIAL NOTES

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Photo Acknowledgements
Fraunhofer-Gesellschaft p. 8
Fraunhofer CSP p. 9
G.tecz Engineering GmbH p. 19, Fig. 2
ingenhoven architects / H.G. Esch p.19, Fig. 3
European Union 2012, PVGIS (map) / topae/Shutterstock (truck) p. 42
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Timo Sigurdsson: p. 75, p. 78

EVENTS IN 2018

WITH PARTICIPATION OF FRAUNHOFER ISE

Zukünftige Stromnetze für Erneuerbare Energien
Berlin, Germany, 30.–31.01.2018

E-World
Essen, Germany, 06.–08.02.2018

EnInnov 2018
Graz, Austria, 14.–16.02.2018

Battery Experts Forum
Aschaffenburg, Germany, 27.02.–01.03.2018

ABXPV / PEROPTO
Rennes, France, 27.02–01.03.2018

9th International Rechargeable Battery Expo
Tokyo, Japan, 28.02.–02.03.2018

Energy Storage Europe
Düsseldorf, Germany, 13.–15.03.2018

Silicon PV, 8th International Conference on Crystalline Silicon Photovoltaics
Lausanne, Switzerland, 19.–21.03.2018

TGA-Kongress 2018
Berlin, Germany, 22.–23.03.2018

Solarex
Istanbul, Turkey, 05.–07.04.2018

CSSC-10 – 10th International Workshop on Crystalline Silicon for Solar Cells
Sendai, Japan, 08.–11. 04.2018

14th International Conference on Concentrator Photovoltaic Systems (CPV – 14)
Puertollano, Spain, 16.–18.04.2018

SPIE Photonics Europe
Strasbourg, France, 22.–26.04.2018

Hannover Messe Industrie
Hanover, Germany, 23.–27.04.2018

Symposium Photovoltaische Solarenergie 2018
Kloster Banz, Bad Staffelstein, Germany, 25.–27.04.2018

EnerStock 2018
Adana, Turkey, 25.–28.04.2018

Berliner Energietage
Berlin, Germany, 07.–09.05.2018

IFAT, Messe für Wasser-, Abwasser-, Abfall- und Rohstoffwirtschaft
Munich, Germany, 14.–18.05.2018

The Battery Show Europe
Hanover, Germany, 15.–17.05.2018

12th SNEC PV POWER EXPO 2018
Shanghai, China, 27.–30.05.2018

HOPV-18
Benidorm, Spain, 28.–31.05.2018

PCIM Europe
Nuremberg, Germany, 05.–07.06.2018

41st IEEE International Conference 2018
Groningen, Netherlands, 10.–13.06.2018

45th IEEE Photovoltaic Specialists Conference
Waikoloa Village, Hawaii, USA, 10.–15.06.2018

Symposium Thermische Solarenergie
Kloster Banz, Bad Staffelstein, Germany, 13.–15.06.2018

E-MRS Spring Meeting
Strasbourg, France, 18.–22.06.2018

Intersolar Europe / Electrical Energy Storage
Munich, Germany, 20.–22.06.2018

Electrical Energy Storage North America
San Francisco, USA, 10.–12.07.2018

DGWF Jahrestagung
Cologne, Germany, 05.–07.09.2018

Internationale ILIAS Konferenz
Luzern, Switzerland, 06.–07.09.2018

Heat Powered Cycles Conference 2018
Bayreuth, Germany, 16.–19.09.2018

World of Energy Solutions 2018 / f – cell 2018
Stuttgart, Germany, 18.–19.09.2018

35th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)
Bruxelles, Belgium, 24.–28.09.2018

4th PSCO
Lausanne, Switzerland, 30.09.–02.10.2018

Chillventa
Nuremberg, Germany, 16.–18.10.2018

VDE-Tec Summit 2018
Berlin, Germany, 20.–21.11.2018

2018 MRS Fall Meeting
Boston, USA, 25.–30.11.2018