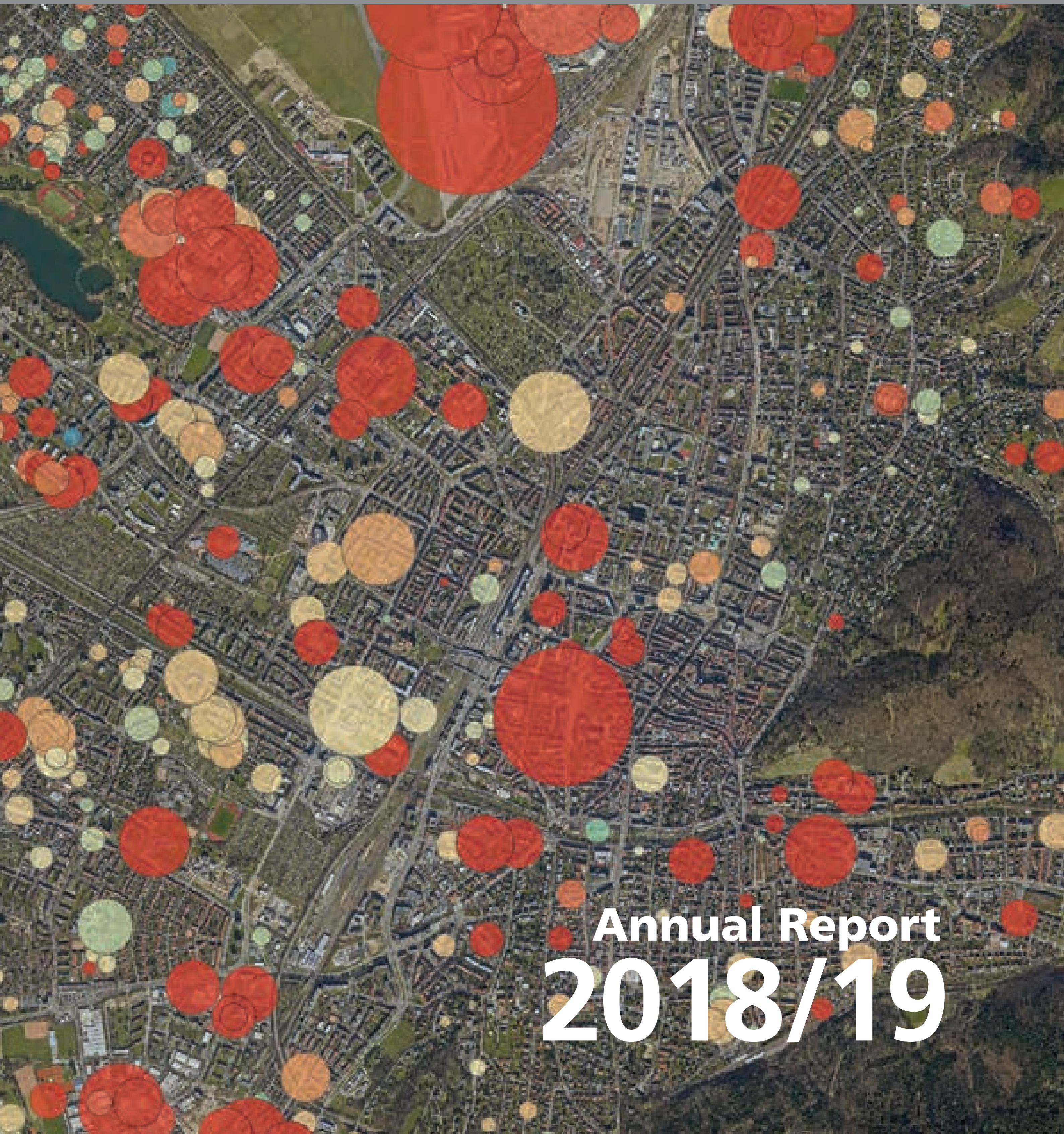
Fraunhofer
ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE



Annual Report 2018/19

Title page: The colored circles in the satellite photo of the inner suburbs of Freiburg im Breisgau, Germany, show the locations of individual PV systems. The area of each circle is proportional to the installed system power. The color code indicates the tilt angle of the modules. It is evident that larger systems often have a similar, usually small, tilt angle. These are typically systems on industrial buildings, which commonly have flat roofs. Smaller PV systems on houses, by contrast, display a wider range of tilt angles. The variation in size, tilt angle and also the orientation causes the systems to generate different amounts of electricity at different times of day. It is important for grid operators to know, as accurately as possible, how much electricity will be fed into the grid at which time of day. Coupling between the electricity, heat and transport sectors will result in more complex inter-sectoral interaction in the future, so that a finely resolved overview of energy supply and demand will become increasingly important. Within its numerous digitalization projects, one of the aspects that Fraunhofer ISE is addressing is therefore the development of modern prediction methods for energy suppy and consumption, and user-friendly control tools.

Annual Report
2018/19

FOREWORD

We can look back on 2018 as a successful year. We experienced slight growth both in the funding of the Institute and in the number of employees.

The major project of energy transformation for all aspects of society, to which we are dedicated, is progressing with increasing intensity into its second phase, in which the coupling of different sectors is becoming relevant. Parallel to the continuing technological development in "Photovoltaics", the demand for comprehensive competence in "Energy Technologies and Systems", in which the Institute also has decades of experience, is accordingly increasing strongly. Technology for system integration of renewable energy sources and for the coupling of electricity, heat and transport is the focus of increasing attention. Against this background, in 2018, we have intensively addressed the development perspective for Fraunhofer ISE and formulated a business and campus development plan for the Institute entitled "Technology and Systemic Solutions for the Global Energy Transformation". It forms the basis for necessary campus development in the near future (see page 20).

In this paper on business development of Fraunhofer ISE, we have also identified topical subjects that will have decisive influence on our work in the context of transforming the energy system. These include digitalization, on which we place special emphasis in this Annual Report (see page 22). We have identified the R&D projects with a digitalization component with an icon . The further trend topics – sector coupling, sustainable mobility, materials engineering and resource efficiency as well as innovative manufacturing procedures – will be accentuated successively in the context of our Public Relations work.

One highlight in "Photovoltaics" was the dedication of our technology platform "PV-TEC – Photovoltaic Technology Evaluation Center" in July 2018, which we had to rebuild completely after a fire in February 2017. We are very glad to be operating this unique service center again as a central activator for transferring innovation over the entire value chain of photovoltaics. The "SiM-TEC – Silicon Materials Technology Evaluation Center" can look back on ten years of successful work, which includes the foundation of the NexWafe spin-off for market introduction of a new, disruptive wafer technology and the materials development for highest efficiency among multicrystalline silicon solar cells.

Strategy audits represent an important tool for strategic orientation of our R&D topics. In 2018, we subjected our photovoltaic technology to an audit and received valuable feedback for further orientation. Beyond technological development, we are currently working – in joint efforts with German and European partners from research and industry – to reestablish PV production in Europe, to achieve technological independence and innovation capacity in this vital energy sector. One important aspect in this connection is consideration and early integration of sustainability and resource efficiency as part of further establishment and expansion of a sustainable energy system.

Adapting to market developments, we have restructured our business areas within "Energy Technologies and Systems": Low-temperature thermal use of solar energy was added to the renamed "Energy-Efficient Buildings" business area and "Solar Thermal Power Plants and Industrial Processes" was extended to include industrial thermal applications of solar energy. The extensive technologies for central and distributed electricity grids have been gathered together in "Power Electronics, Grids and Intelligent Systems". The strategic expansion of our R&D work on electric storage from battery systems also to the cell level, which had been announced the previous year, has now found its place in "Hydrogen Technologies and Electric Storage Systems".

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

The planned establishment of a new "Competence Center for Batteries and Energy Storage Systems", in cooperation with the Fraunhofer Institute for High-Speed Dynamics EMI, VDE Renewables GmbH and with Federal and State funding support, is gaining momentum. In 2019, the building construction as well as relocation and new installation of the relevant technical equipment is foreseen at a new site in Freiburg.

Heat pumps are vital to the success of the energy transformation in the heat sector. Last year, we had the opportunity to organize a special presentation on the potential and current challenges concerning heat pumps at the leading trade fair in this sector, Chillventa in Nuremburg, Germany. The presentation was based on many years of experience at Fraunhofer ISE along the complete value chain for heat pump technology, from the development of materials and components together with partners and clients from industry and research, through field tests and laboratory investigations, to consideration of the equipment in the entire energy system. A current research focus is the application of environmentally acceptable refrigerants like propane in heat pumps.

The new edition of the Fraunhofer ISE Study on the levelized cost of electricity, including market scenarios up to 2035, clearly shows that the levellized cost of electricity from renewable energy sources will fall continuously and no longer present any obstacle to CO_2-free electricity generation. The levelized cost of electricity from newly installed photovoltaic systems and onshore wind energy plants at favorable sites is already lower today than that for new power plants based on fossil fuels. This trend will continue in future.

On commission to the German Federal Ministry of Transport and Digital Infrastructure (BMVI), Fraunhofer ISE cooperated with partners to prepare a study on the gigawatt potential of electrolysis, entitled "Industrialization of Water Electrolysis in Germany: Opportunities and Challenges for Sustainable Hydrogen for Transport, Electricity and Heat". It demonstrates how the necessary industrial production capacity for electrolyzers can be established in coming years. On the assumption that the climate protection goals of the German Federal Government are reached, an installed system power in the range of tens to hundreds of gigawatts is predicted for Germany alone.

In the summer of 2018, the Presidential Board of the Fraunhofer-Gesellschaft approved the formation of the "Integrated Energy Systems" Cluster of Excellence. Together with Fraunhofer IEE and Fraunhofer ISI as the two other core Institutes, and with further partner Institutes, central questions for a successful energy system transformation will be addressed at an interdisciplinary level.

In autumn, we rejoiced together with the University of Freiburg over great success in the Excellence Strategy competition. Fraunhofer ISE is actively participating in one of the two Excellence Clusters, "livMatS:Living, Adaptive and Energy-autonomous Materials Systems".

We extend our sincere gratitude to our Board of Trustees, auditors, scholarship donors, contact persons und funding sources in the Ministries at the Federal and State levels and all of our project partners for support and funding of Fraunhofer ISE as well as good cooperation. We look forward to further cooperation toward consistently transforming the energy system in Germany and globally – with the goals of achieving a sustainable energy supply based on renewable sources and retaining German and European technological independence in this field.

Prof. Hans-Martin Henning　　Dr. Andreas Bett

GUIDING PRINCIPLES OF FRAUNHOFER ISE

VISION

Our driving motivation is to secure the livelihood of present and future generations and protect our natural resources.

With our pioneering research and development work, we hold a leading role internationally in the field of renewable energy systems and technologies. This enables us to contribute significantly to creating a sustainable, economic, secure and socially just energy supply worldwide, paving the way for an energy supply based exclusively on renewable energy sources.

MISSION

Fraunhofer ISE carries out applied energy research. Through excellent research results, successful projects with industry partners, spin-off companies and global cooperations, we shape the transformation of the global energy system.

Together with companies, we transform original ideas into innovations that benefit society and strengthen both the German and European economy. With our technological and system-oriented approach, we support our customers through to the industrial implementation and successful market entry. Our scientific work ranges from materials research through to system integration.

OUR PRINCIPLES

Employees and Cooperation
Fraunhofer ISE's success relies on the knowledge, enthusiasm and diversity of our employees. We place great importance on their professional and personal development and work actively to promote equal opportunity. By offering flexible working conditions, we support the compatibility of work and private life. Our working relationship is based on trust and mutual appreciation, guided by respect and responsibility. Our transparent and cooperative working environment promotes trust as well as motivation and self-determination.

Sustainability
In fulfilling our tasks, we are aware of our responsibility to society and the natural environment. We orient ourselves on the principles of a sustainable development. These make up an integral part of our research and development goals as well as our internal processes. The protection of our resources through closed-loop material cycles is an essential component of a sustainable energy supply.

Customers
We tailor our research services to address our customers' needs. We reach out to our customers, understand their challenges and successfully develop long-term solutions together. Our customers profit from our preparatory research and our infrastructure. We carry out our work professionally and in a targeted manner and foster a trusting and reliable working relationship with our customers.

We value long-term partnerships which are based on mutual respect and integrity.

Science
We strive for scientific excellence. The safeguarding of good scientific practice is for us self-evident. We publish our scientific results in renowned magazines and journals and present them at conferences worldwide, actively participate in committees and register patents.

We cooperate with the University of Freiburg as well as other national and international universities and institutes. We teach and assist scientific education by initiating and supervising the work of students and doctoral students.

Quality and Processes
Our objective is to provide high-quality results. We continually optimize our internal processes with regard to the effective and efficient use of resources. Our quality management is subject to regular external audits and is certified according to international standards.

Networking
Together with our sister institutes in the Fraunhofer-Gesellschaft, we help shape the energy system transformation. We network closely with actors on the national and international markets as well as cultivate cooperative partnerships with science and industry worldwide. The participation in associations and committees helps us to align our key research areas. The active inclusion of society and the participation in political discussions enables us to shape the future with our vision in mind.

CONTENT

Articles on digitalization

ORGANIZATIONAL STRUCTURE

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 Technologies 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 Technologies and Systems

- Energy-Efficient Buildings
- Solar Thermal Power Plants and Industrial Processes
- Hydrogen Technologies and Electrical Energy Storage
- Power Electronics, Grids and Smart Systems

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).

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

Institute Directors

Prof. Hans-Martin Henning | Phone: +49 761 4588-5134
Dr. Andreas Bett | Phone: +49 761 4588-5257

Heads of Photovoltaics Division

Prof. Stefan Glunz | Phone: +49 761 4588-5191
Dr. Ralf Preu | Phone: +49 761 4588-5260
Dr. Harry Wirth | Phone: +49 761 4588-5858

Heads of Energy Technologies and Systems Division

Dr. Christopher Hebling | Phone: +49 761 4588-5195
Dr. Peter Schossig | Phone: +49 761 4588-5130
Dr. Olivier Stalter | Phone: +49 761 4588-5467

Business Administration

Dr. Alexandra Heßling | Phone: +49 761 4588-5917

Facility Management

Jochen Vetter | Phone: +49 761 4588-5214

Press and Public Relations

Karin Schneider M.A. | Phone: +49 761 4588-5150

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 program of Fraunhofer ISE (Status: 31st December 2018).

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 26,600 staff are qualified scientists and engineers, who work with an annual research budget of more than 2.5 billion euros. Of this sum, more than 2.1 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 – 1826), the illustrious Munich researcher, inventor and entrepreneur.

EXTERNAL BRANCHES, COOPERATION, NETWORKS

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 51 research institutes, companies and organizations around the world. Among other memberships, it is a member of the German ForschungsVerbund Erneuerbare Energien (FVEE – Research Association for Renewable Energy), the European Technology and Innovation Platform (ETIP) and the Association of European Renewable Energy Research Centers (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).

External Branches

- Fraunhofer ISE Laboratory and Service Center, Gelsenkirchen LSC: development of transparent electrodes based on nano-wires and measurement technology for photovoltaics
- 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, USA
- 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 Alliance for Energy, but has also been responsible for its management since its establishment in 2003. The Institute Director, Prof. Hans-Martin Henning, is the 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, Energy Storage, Energy Efficiency, Energy in Digital Context, Energy Systems and Energy in Urban Context.

Further Networking within the Fraunhofer-Gesellschaft

- Fraunhofer Alliances: Batteries, Building, 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 transdisciplinary 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 Freiburg University's "Institut für Nachhaltigkeit und Technische Systeme" (INaTech – Institute for Sustainability and Technical Systems), which addresses sustainable materials, energy systems and resilience.

1 *Fraunhofer ISE cooperates closely with the Technical Faculty of the University of Freiburg.*

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 1266 (600 full-time equivalent).

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, 87 % of the Institute`s funding originates from 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 Technologies and Systems – address five market-oriented business areas:

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

- Business Area "Energy-Efficient Buildings"
- Business Area "Solar Thermal Power Plants and Industrial Processes"
- Business Area "Hydrogen Technologies and Electrical Energy Storage"
- Business Area "Power Electronics, Grids and Smart Systems"

Services in Accredited Laboratories

In addition, Fraunhofer ISE offers independent testing and certification services. 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)

R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of more than 16 000 m^2 and highly 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 Electrolysis, Fuel Cells 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

1 *Main building of Fraunhofer ISE in Freiburg.*

RESEARCH COMMISSIONED BY CLIENTS

Research that is commissioned by clients from industry, science and politics is the primary activity of Fraunhofer ISE. We cooperate with numerous and diverse project partners in this activity. For some small and medium-sized enterprises, we replace an in-house research department. Large enterprises profit from our specific know-how and our excellent technical facilities. We also advise cities, local government authorities and educational institutions and carry out e. g. feasibility studies and modelling. We offer customized solutions to meet the requirements of our clients.

Contractually agreed research and development projects with our partners from industry and research form the core of our work. As the largest solar research institute in Europe and with more than 30 years of experience, we are well-connected within this sector, with political institutions and with professional associations, so that our clients also benefit from cooperating with us via strategic partnerships and innovation clusters.

From the Initial Idea to the Marketable Product

Depending on requirements, Fraunhofer ISE accompanies its project partners with a selection from its broad spectrum of competence from the initial idea to the marketable product. Together with our clients, we conduct research on new materials and components, develop new methods, prepare simulations and models, and carry out proofs of principle.

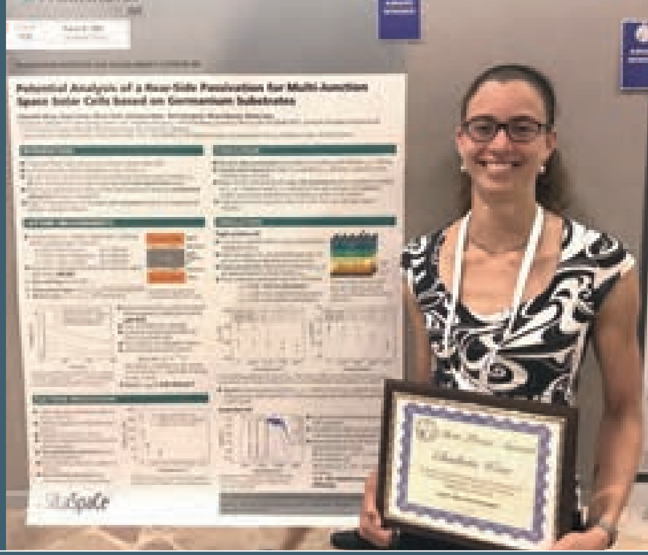
We develop prototypes and small series of new components and equipment, transfer the production processes to production scale, apply measurement technology for analysis and prepare proofs of concept. We also support our clients during the market introduction phase. We provide advice during planning processes, prepare studies and assess possible systems designs. In our accredited laboratories, we support research with testing and certification services, which guarantee that products can be sold in the market. We offer monitoring and quality control for instruments and systems in the field.

Expertise and Experience

After more than 30 years in the market, Fraunhofer ISE can draw on profound knowledge of the market and extraordinary professional know-how. An important advantage of the Institute is its first-class technical infrastructure. The most modern laboratories and equipment for the entire spectrum of our activities are available to our clients over an area of more than 16 000 m^2.

Successful completion of R&D projects demands not only professional competence but also goal-oriented work and reliable project management with established processes. In addition, we guarantee confidentiality and offer professional agreements regarding the rights to use patents and licences. Quality control of our work has high priority, so that we can always tune our work optimally to the demands of the market. External audits every year ensure that high standards are maintained in this regard. In addition, we regularly conduct surveys among our clients. We are proud of and simultaneously inspired by feedback from our project partners indicating their great satisfaction.

PRIZES AND AWARDS



Dr. Christoph Siedle, Stefan Reichert, Benjamin Stickan, Moritz Bader | 6. Zukunftspreis der Privaten Stiftung Ewald Marquardt für Wissenschaft und Technik | Paper "Universelle hochdynamische Umrichterregelung für ein- und dreiphasige Systeme im Netzparallel-, Insel- und unterbrechungsfreien USV-Betrieb" | 16.03.2018 | Bulzingen, Germany

Dr. Elmar Lohmüller | "BBr_3 Diffusion with Second Deposition for Laser-Doped Selective Emitters from Borosilicate Glass", **Tim Niewelt** | "Taking Monocrystalline Silicon to the Ultimate Lifetime Limit", **Dr. Florian Schindler** | "Towards the Efficiency Limits of Multicrystalline Silicon Solar Cells" | SiliconPV Awards 8. SiliconPV | 18.03.2018 | Lausanne, Switzerland

Dominik Noeren, Simon Bürer, Gerhard Stryi-Hipp | Best Poster Award | "Speicherkapazitäten & DSM-Potenziale von E-Carsharing-Flotten" | Lab2Reality | 12.04.2018 | Berlin

Juan Francisco Martínez Sánchez | Student Award | Presentation "4-Terminal CPV Module Capable of Converting Global Normal Irradiance into Electricity" | 14. International CPV-Conference | 16. – 18.04.2018 | Puertollano, Spain

Theresa Trötschler | Best Poster Award | "3D Grain Structure and Defect Analysis Based on Optical and PL Measurements of As-Cut-Wafers" | 10th International Workshop on Crystalline Silicon for Solar Cells | 18.04.2018 | Sendai, Japan

Andreas Fell, Sebastian Meier, Malcolm Abbott, Keith Mcintosh | Best Poster Award | "Comprehensive Electro-Optical Device Simulation of Bifacial PERC and PERT Silicon Solar Cells Enabled by Interfacing SunSolve and Quokka3" | SNEC | 19. – 21.04.2018 | Shanghai, China

Dr. Frank Dimroth, Dr. Martin Hermle | GreenTec Award (2nd place in Energy category) | "Höchsteffiziente Solarzellen mit 18 % mehr Leistung" | 13.05.2018 | Munich, Germany

1 *WCPEC-7 Best Poster Award winner Dr. Charlotte Weiss.*

Marius Holst | Innovation Award Deutscher Wasserstoff- und Brennstoffzellen-Verband (DWV) | M. Sc. thesis "Technische Untersuchung des Abwärmenutzungspotenzials von Power-to-Gas-Anlagen" | 30.05.2018 | Salzgitter, Germany

Dr. Matthias Breitwieser | Innovation Award Deutscher Wasserstoff- und Brennstoffzellen-Verband | Ph. D. thesis "Neues Verfahren für die Herstellung von Elektrolyten für Brennstoffzellen oder PEM-Elektrolyseure" | 30.05.2018 | Salzgitter

Dr. Charlotte Weiss | Best Poster Award Space PV Technologies | "Potential Analysis of a Rear-Side Passivation for Multi-Junction Space Solar Cells based on Germanium Substrates", **Jonas Huyeng** | Best Poster Award Homojunction Devices and Technologies | "Advancements in the Utilization of Screen Printed Boron Doping Paste for High Efficiency Back-Contact Back-Junction Silicon Solar Cells" | WCPEC-7 | 10. – 15.06.2018 | Waikoloa, Hawaii, USA

Nicolas Carbonare | Scientific Paper Award | "Clustering the Occupant Behavior in Residential Buildings: A Method Comparison" | IBPSA Germany/ BauSim Austria 2018 | 26.09.2018 | Karlsruhe, Germany

Monika Bosilj | 3rd place Poster Award Biotechnology | "Sustainable Hydrothermal Carbons for Biorefinery-related Catalysis" | N.I.C.E. Conference | 14. – 17.10.2018 | Nice, France

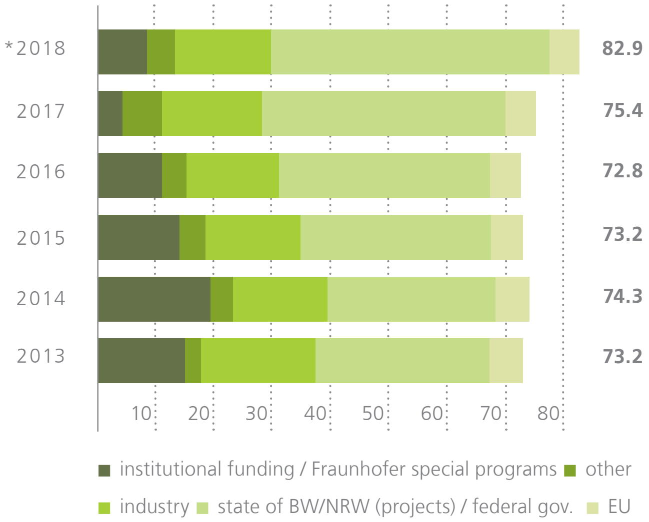
Claudia Lisa Schilling | Robert-Mayer Young Academics Award | M. Sc thesis "Entwicklung hochreflektierender Kontaktschichten für III-V-Konzentratorsolarzellen" | 17.10.2018 | Freiburg , Germany

Thaddäus Weniger | Research Award Deutscher Verband des Gas- und Wasserfachs | B. Sc thesis "Labortest einer Netzdienlichen BHKW-Regelung" | 23.10.2018

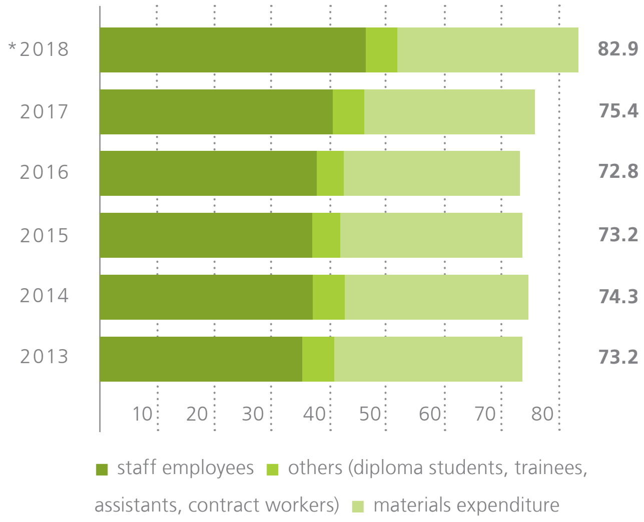
Lukas Wagner | 2nd place Ideas competition "Energie-Campus" | Research on perovskite solar cells | Stiftung Energie und Klimaschutz | 23.11.2018

THE INSTITUTE IN FIGURES

Income in million euros**

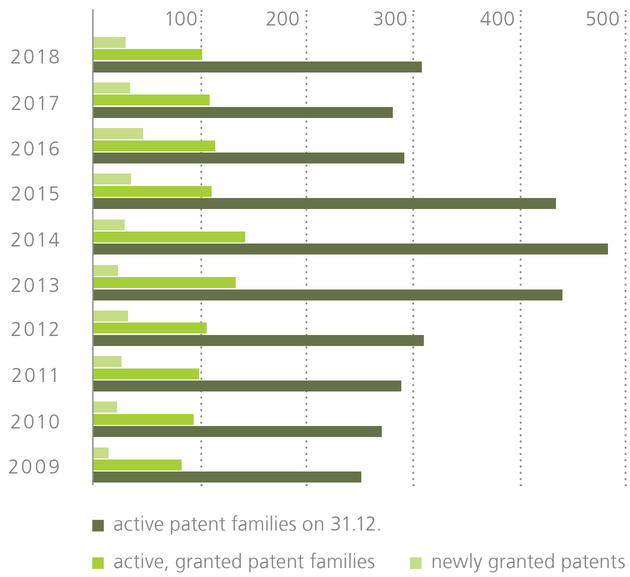


Expenditure in million euros**

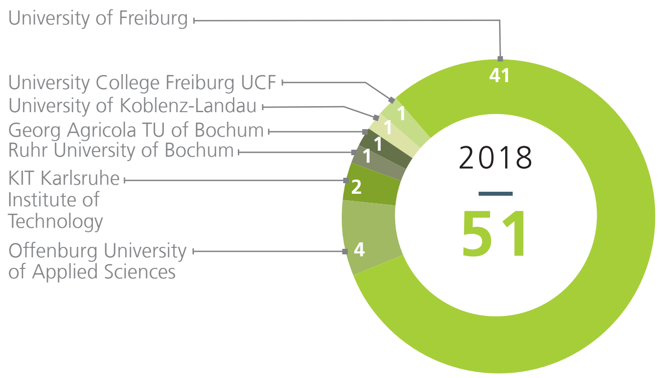


**preliminary* ***without investments – the total budget 2018 (incl. investments) totalled 100.1 million euros.*

Patents

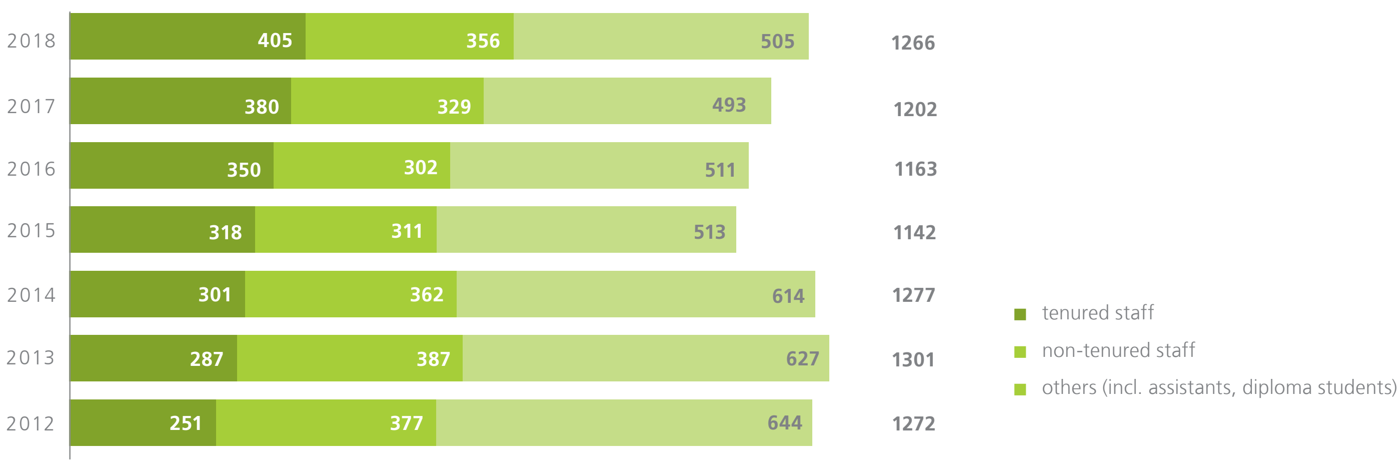


Lecture Courses and Seminars

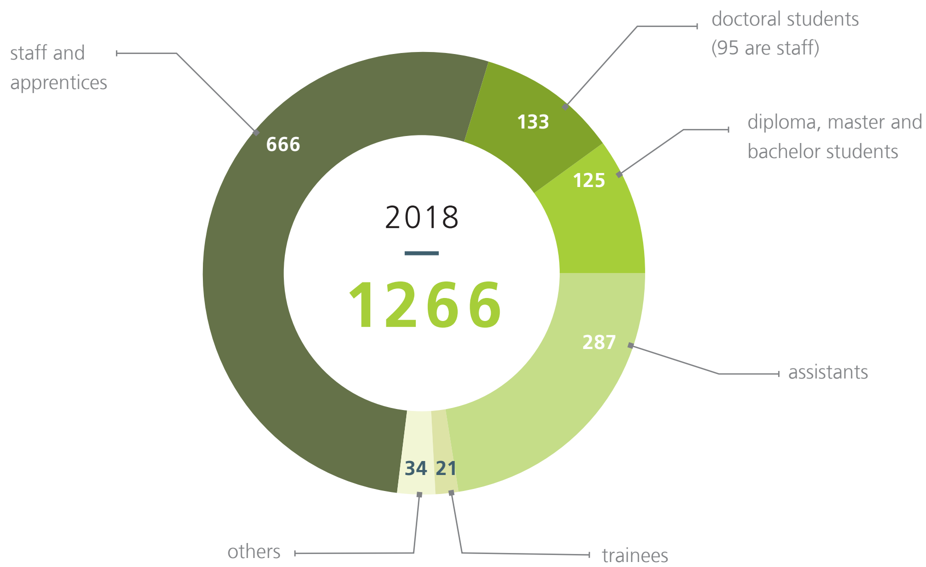


39 scientists of Fraunhofer ISE give regular lectures at universities in addition to their research work.

Personnel



Personnel 2018



DOCTORAL THESES

Shankar Bogati
"Development and Description of Photochromic Devices Prepared by Sputtering"
University of Freiburg, 2018

Marouane Boudhaim
"Optical and Thermal Performance of Complex Fenestration Systems in the Context of Building Information Modelling"
Institut National des Sciences Appliquées de Strasbourg (INSA), 2018

Mehmet Elci
"Smarte und Dezentrale Solare Fernwärme" (Smart and Decentralized Solar District Heating)
Karlsruhe Institute for Technology (KIT), 2018

Fabian Eltermann
"Validierung von Methoden für den Zuverlässigkeitsnachweis von Konzentratorsolarzellen" (Validation of Methods to Prove the Reliability of Concentrator Solar Cells)
University of Freiburg, 2018

Sebastian-Johannes Ernst
"Development and Characterization of Advanced Materials for Heat Transformation Applications"
Technical University of Kaiserslautern, 2018

Torsten Geipel
"Electrically Conductive Adhesives for Photovoltaic Modules"
University of Hannover, 2018

Raphael Hollinger
"Gepoolte PV-Heimspeicher zur Bereitstellung von Primärregelleistung" (Pooled PV Home Storage Units to Provide Primary Control Power)
Technical University of Braunschweig, 2018

Noha Saad Hussein
"Effects of Building Refurbishment on a District's Energy System: Optimization of the Deployment and Operation of Heat, Power and Sector Coupling Technologies"
University of Freiburg, 2018

Peter Jakob
"Verbesserungspotentiale für Silikonoptiken in der konzentrierenden Photovoltaik" (Improvement Potentials for Silicone Optics in Concentrating Photovoltaics)
University of Freiburg, 2018

Manuel Lämmle
"Thermal Management of PVT Collectors: Development and Modelling of Highly Efficient Glazed, Flat Plate PVT Collectors with Low Emissivity Coatings and Overheating Protection"
University of Freiburg, 2018

Sebastian Meier-Meybrunn
"Development and Characterization of p-type PERT Solar Cells"
University of Freiburg, 2018

Björn Müller
"Unsicherheiten von Ertragsprognosen für Photovoltaik-Kraftwerke unter besonderer Berücksichtigung langfristiger Variationen des Solarstrahlungs-Potenzials" (Uncertainties of Yield Predictions for Photovoltaic Power Plants, Particularly Taking Long-term Variations of the Solar Radiation Potential into Account)
University of Kassel, 2018

Sebastian Nold
"Techno-ökonomische Bewertung neuer Produktionstechnologien entlang der Photovoltaik-Wertschöpfungskette" (Techno-economic Evaluation of new Production Technologies along the Photovoltaic Value Chain)
University of Freiburg, 2018

Emile Tabu Ojong
"Characterization of the Performance of PEM Water Electrolysis Cells Operating with and without Flow Channels, Based on Experimentally Validated Semi-empirical Coupled-Physics Models"
Brandenburg University of Technology, Cottbus-Senftenberg, 2017

Malte Otromke
"Base Catalysed Hydrothermal Reformation of Kraft Lignin"
Karlsruhe Institute for Technology (KIT), 2018

Annika Spies
"Numerical Simulations and Advanced Characterization of Organic Solar Cells"
University of Freiburg, 2018

Ursula Wittstadt
"Experimentelle und modellgestützte Charakterisierung von Adsorptionswärmeübertragern" (Experimental and Model-supported Characterization of Adsorption-based Heat Exchangers)
Technical University of Berlin, 2018

Annie Zirkel-Hofer
"Enhanced Dynamic Performance Testing Method for Line-concentrating Solar Thermal Collectors"
Technical University of Braunschweig, 2018

Frank Zobel
"Entwicklung des Float-Zone-Verfahrens zur Herstellung von Siliziumeinkristallen für solare Anwendungen" (Development of the Float-zone Process to Produce Monocrystalline Silicon for Solar Applications)
University of Halle-Wittenberg, 2018

1 *Honoring the doctoral students at the Fraunhofer ISE annual meeting 2018: from left to right: Shankar Bogati, Manuel Lämmle, Ursula Wittstadt, Sebastian Meier-Meybrunn, Andreas Lorenz (graduation in 2017), Emile Tabu Ojong, Björn Müller, Annie Zirkel-Hofer, Mehmet Elci.*

CAMPUS DEVELOPMENT AND TOPICAL SUBJECTS

Question: **Prof. Henning, Dr. Bett, last year you addressed how the R&D content and campus of Fraunhofer ISE would be developed in future. What was the background and which accents did you place?**

Henning: The actual trigger was that an opportunity arose in the immediate vicinity of our current campus to develop it further. At the same time, the future direction that R&D topics at Fraunhofer ISE will take is driven by our energy systems analyses and modelling of the energy transformation, including the necessary technological routes. The business plan is thus also guided by the questions: What will a future, sustainable energy system look like? What are key technologies? Which technologies are we addressing here at Fraunhofer ISE and where should we intensify our efforts? When all of these questions are taken into account, it is finally a matter of making best possible use of the opportunities that are offered.
Bett: Almost all energy system scenarios show that, alongside wind energy, photovoltaics will be the most important pillar of the future energy supply. But also questions of increased flexibility, of sector coupling, play a central role. And we continue to need hydrocarbons or other synthetic materials produced with renewably generated electricity, a topic in which hydrogen as a fuel and electrolysis as a process are highly significant. These are all topics on which we are already working, but for which we see the perspective of expanding our infrastructure.

Question: **The business plan identifies five topical subjects which already influence the work of Fraunhofer ISE and will continue to do so. What are they?**

Bett: They are digitalization, sector coupling, sustainable mobility, materials engineering and resource efficiency and innovative production processes. Digitalization affects all topics. If we take future production technology in photovoltaics as an example, digitalization and sustainable production are the main drivers. If we want to have PV production in Europe, digitalization will play a decisive role. Here, we are talking about machine networking, machine-based learning, interaction and the vision of fully automated production with extremely good quality control. These are high-tech developments for which we are well prepared at Fraunhofer ISE.

Question: **Does the topical subject of digitalization also offer the potential to accelerate new fields of application?**

Bett: Yes, we will see greater integration of photovoltaics into our built environment. We are now talking about "xPV", about "integrated PV", in which we extend beyond considering only the individual module. Up to now, the main focus was on reducing costs, which was achieved in the application in large-area power plants. To massively increase the amount of installed photovoltaics, we will also have to offer technical solutions in future which can be located in our urban environment. That means that topics like aesthetics and acceptance by the population also have to be considered, that the modules must be designed more flexibly, rather than concentrating only on the maximum power output. The focus here is on obtaining the maximum energy yield that can be achieved under given boundary conditions. Examples include building-integrated photovoltaics, but also PV on roads, on cars, generally in the mobility and other sectors. This demands intelligent and flexible production, which is not yet the case in the photovoltaic industry.

Question: **The role of digitalization in the energy transformation was also the main topic of this year's annual conference of the German Research Association for Renewable Energy FVEE. Which aspects were discussed there?**

Henning: Digitalization is important not only for manufacturing technology for photovoltaics, battery production and other technologies, but also for the operation of the energy

system. Relevant topics include predictions of electricity generation, which affect grid operation, and data-based methods will also become more important for the distribution and transport of energy. Data-based procedures will be essential for trading, sales and distribution, for the entire energy market. Finally, new business models for marketing and management of energy flows are emerging in the context of digitalization. And that means that new actors are affected, down to the demand and consumption stage. Fraunhofer ISE is addressing aspects of digitalization in all of these segments. A practical illustration is given by the mondas company, a recent spin-off from the Institute in the technical building plant sector. The enterprise gathers data from many similar building technology systems in a cloud, in order to learn optimized building operation by applying Big Data methods.

Question: **Fraunhofer ISE is strongly promoting the concept of photovoltaic production in Europe. How can this goal be achieved?**

Bett: The rapid development of the global PV market offers a great opportunity for the European industry. Apart from the aspects of “intelligent and flexible” PV for new application fields that I have already mentioned, Europe also has a head start concerning innovation to achieve sustainability goals. Sustainability must be discussed regarding the entire life cycle of a module, the production process and its effect on logistics. With production costs being so low today, the costs of logistics and the associated emission factors are becoming increasingly relevant. The same applies to module recycling, so that a closed-loop economy is achieved. In Europe, we have the high-quality production technology that is needed to address precisely these topics. Now we have the chance to keep the technological lead and innovative competence for this extremely important future market in Europe, and simultaneously to make an important contribution to reducing CO_2 emissions.

Question: **The Fraunhofer Energy Alliance has formulated a white paper on technological sovereignty. What is its message to politics?**

Henning: The important message is that we have climate protection goals on the one hand, which are formative for the directions that are taken by politics and society at large. However, we must also keep the aspect of competitiveness in mind. The “energy-political triangle” that is derived from the German energy economy law comprises the aspects of supply reliability, environmental acceptability and economic viability. It is really too narrow-minded to consider that “competitiveness” refers only to supplying energy for the lowest costs. If the broader perspective of long-term sustainability is taken, then it also becomes important to ensure that technological competence is retained in Europe to maintain independence. The term “competitiveness” encompasses not only economic viability but also innovative competence and a long-term capacity to compete. And these aspects predestine the topic for Fraunhofer.

Question: **Prof. Henning, you are the Speaker of the Alliance for Energy and now also for the newly created Fraunhofer Cluster of Excellence for Integrated Energy Systems INES. What is the task of the cluster?**

Fraunhofer has created Clusters of Excellence to tap the synergy potential between thematically profiled, individual Institutes by strategic networking. The goal is to promote specific topics internationally and to conduct joint, cutting-edge research within these fields. Several Fraunhofer Institutes are working together on a long-term basis to achieve this goal; this is happening within the framework of strategic road maps for system-relevant innovations.

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

ENERGY TRANSFORMATION – PARADIGMATIC CHANGE AND DIGITALIZATION

"The Energy Transformation – Intelligent and Digital" was the title of the most recent annual conference of the German Research Association for Renewable Energy FVEE. German non-university research institutions for renewable energy discussed the many facets and potentials of digitalization, which has been identified as both an "enabler" and a "driver" of the energy transformation. It plays a key role in finding solutions for decentralization and achieving flexibility, as well as in the efficient use of energy and resources.

Due to the volatility of electricity generated by photovoltaics and wind turbines, implementing the energy transformation will be accompanied by a paradigmatic change in the supply model. The provision of energy as required by large power plants will be replaced by a system in which equilibrium is continually maintained between supply and consumption by complex interaction between time-matched energy generation, sector coupling between electricity, heat and transport, temporary application of flexible generation systems, and storage units. The integration of modern prediction methods for generation and consumption will complement the organization and management of this more complex system. This whole constellation is almost inconceivable without wide-ranging application of digitalization technology and methods.

Digitalization is the "enabler" when it is a matter of managing the complex system and the complex interactions of numerous technical components in the system and actors in the market. It makes efficient, intelligent usage of infrastructure and hardware feasible. Digitalization is the "driver" when there is a need to transfer new technical potential into practice, to offer new services and to introduce new business models. Methods and application fields for digitalization extend over all aspects of energy supply, from generation, through grids, trading and distribution, to consumption and production.

Digitalization is also playing an increasingly important role in energy research. Power electronics is a fundamental technology for digitalization. The smart grid demands interconnected inverter systems. Smart inverters will become key elements of the future electricity systems. They will compensate structural changes in the electricity grid by an integrated management strategy for grid shortfalls. Communications are essential for operating the grid, the market and technical systems. An increasingly distributed grid management system demands new system services for grid operation. The simulation, dimensioning and quality control of decentralized PV-battery stand-alone grids are based on digitalization. Battery systems are controlled by smart inverters and make a higher degree of autonomy feasible. The operation management strategies of hydrogen supply systems are almost inconceivable without digitalization.

In photovoltaic manufacturing, processes based on artificial intelligence can improve the product quality. For instance, autonomously learning image recognition processes can predict solar cell parameters. Yield analyses for cells and modules become feasible by machine-based learning. The parameters for battery cell production can be improved by applying digital twins.

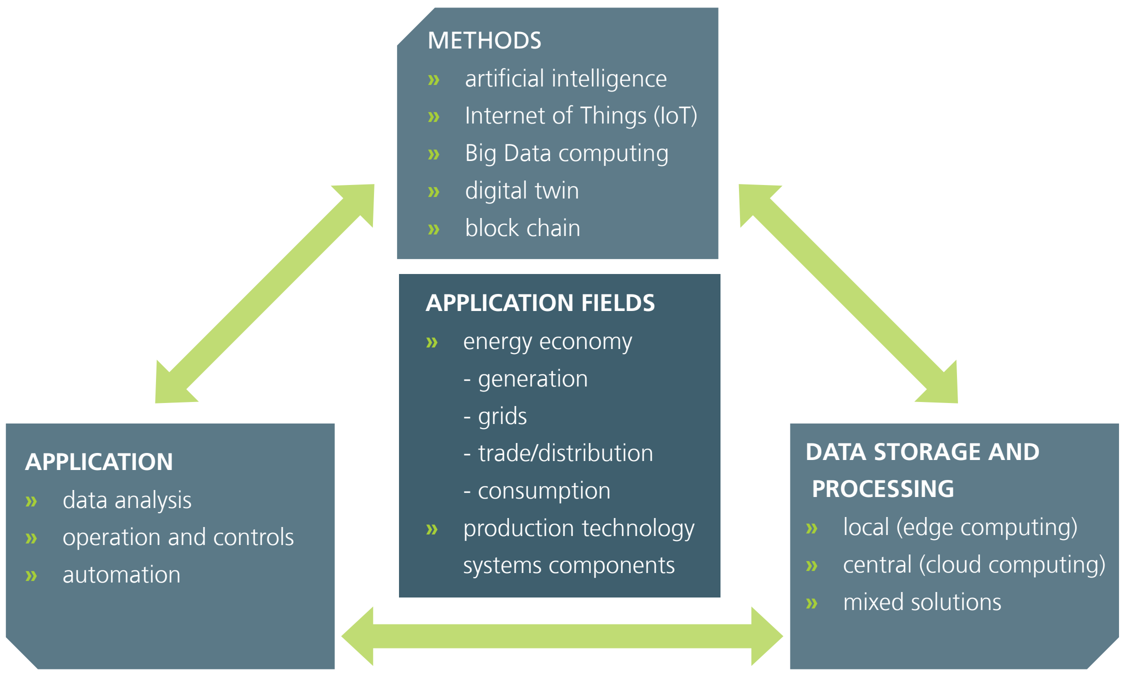
For applications in the "Internet of Things (IoT)", technologies are being developed which will enable the integration of energy supply and data communications in a single component, with highly efficient solar cells or organic PV as the energy supply.

In the automation of building services, the "digital building twin" or Building Information Model (BIM) will make use of big data to optimize the operation of building technical services and thus better meet requirements on comfort and energy efficiency. The operation of heat pumps in interconnected systems can be optimized technically, economically and ecologically by digitalization. The schedules for solar thermal power plants can be optimized by machine-based learning that draws on long-term meteorological data.

Digitalization is a prerequisite for sector coupling at the regional level. For example, it is an integral component in the pioneering "EnStadt:Pfaff" project in Kaiserslautern, where a sustainable quarter for technology, health and residence, including a "Living Lab", is being established on the former manufacturing site of Pfaff sewing machines. Fraunhofer ISE is playing a leading role in this process.

The possibilities which digitalization offers both for technological development and also for sector coupling have certainly not been fully exploited yet. The development is only just starting in many areas. And ICT security and the resilience of the energy systems play a major role in all of them. In this Annual Report of Fraunhofer ISE, we have used this symbol to identify the R&D topics where digitalization is playing a decisive role.

Dimensions of Digitalization

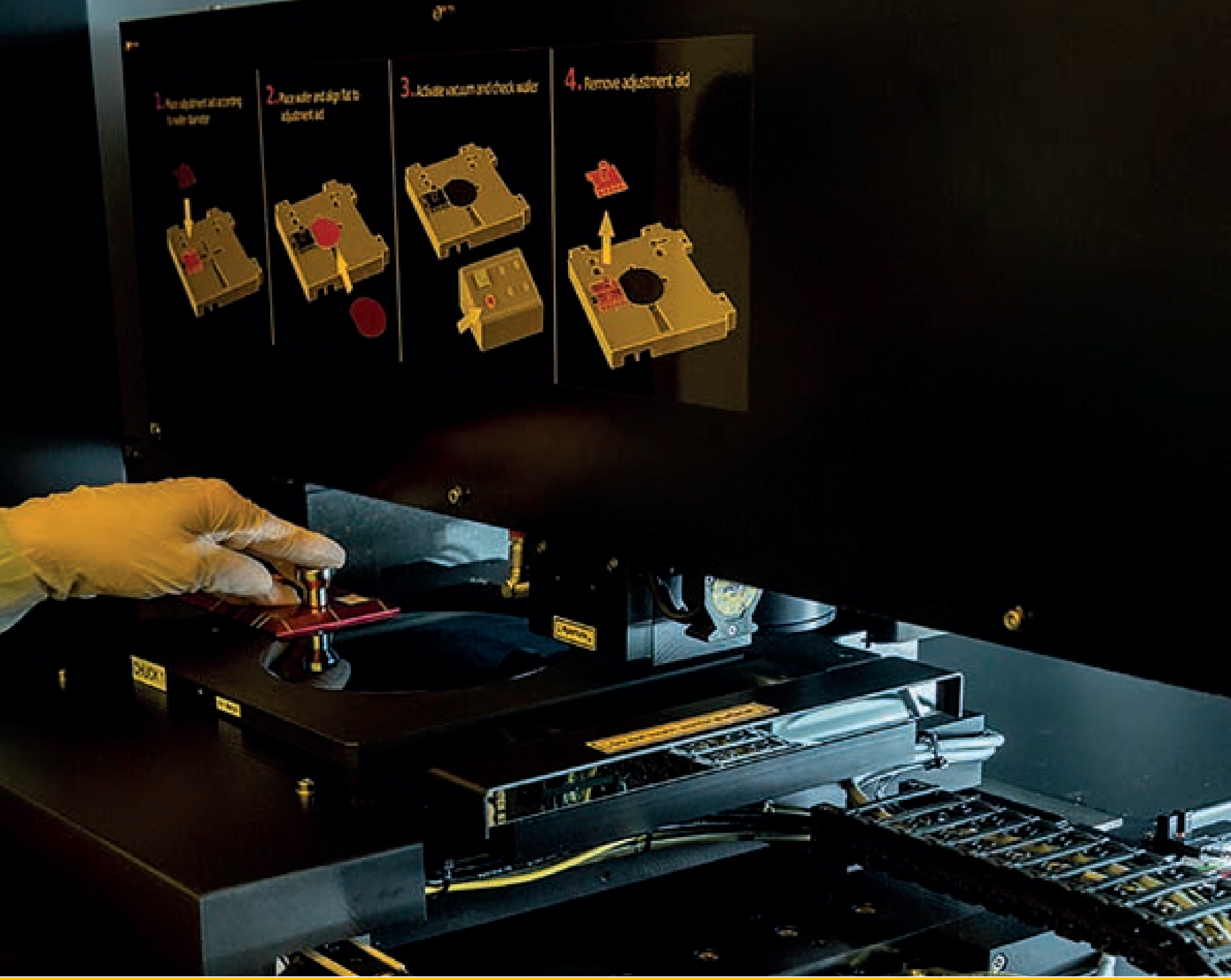


PHOTOVOLTAICS

The transformation of our energy supply system from fossil to renewable energy sources took shape at the Climate Change Conference in Paris in 2015. There, 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. Almost all energy system scenarios indicate that photovoltaics (PV), together with wind energy, will be a central pillar for an economically and ecologically achievable energy supply in the future. Against this background, the PV market will continue to grow rapidly. At the end of 2017, PV power amounting to about 400 GW was installed. At its 2018 meeting, the Global Alliance of Solar Energy Research Institutes (GA-SERI), of which Fraunhofer ISE is a member together with NREL (USA) and AIST (Japan), estimated that 1 terawatt of photovoltaics would be installed globally within the next four years. The dominating cost share of PV power plants, the investment costs, has been decreasing since 2006 by an average of about 13 % per year, in total by 75 %, due to technological progress, scaling and learning effect. In Germany, competitive levelized costs of electricity of 4 to 5 Euro cents per kWh can be achieved today.

i Laser exposure unit for mask-free photolithographic structuring of wafers for highly efficient silicon and III-V solar cells.

Research and development have made essential contributions to this success story. Fraunhofer ISE contributes to continuous improvement in efficiency and use of material resources with its excellent R&D results. Central keywords include the contact passivation technology (Tunnel Oxide Passivated Contact - TOPCon) that was developed at Fraunhofer ISE and the

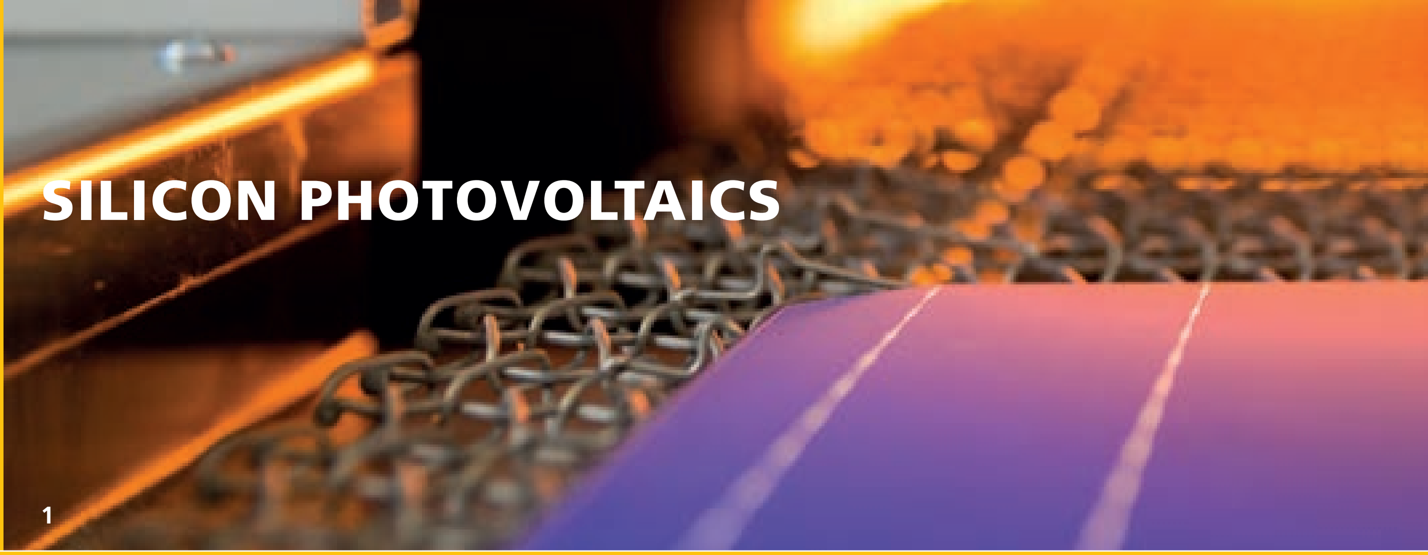


development of special high-performance silicon, which forms the basis for new record solar cell efficiency values. Great progress in the development of monocrystalline material was also made at the Center for Silicon Photovoltaics (CSP) located in Halle. Our R&D work on wafering is carried out in the 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. In the summer of 2018, we were able to resume operation of PV-TEC, where the main laboratory had been destroyed by a fire in the previous year.

In addition, Fraunhofer ISE further develops successful procedures for accurate characterization and yield analysis of cells and modules. Our accredited calibration laboratory, CalLab PV Modules, achieves 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 and a record efficiency value of 41.4 % has been achieved for a module. We apply our long-term experience with the production of multi-junction solar cells to produce a monolithic multi-junction solar cell of GaInP/GaAs/Si based on a tandem concept with an efficiency value of 33.3 %. This promising technology demonstrates how the Auger limit of 29.4 % for single-junction silicon solar cells 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



336
Total staff

97
Journal articles and contributions to books

99
Lectures and conference papers

7
Newly granted patents

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 levelized cost of electricity 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 m^2 of 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 technological 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 are extremely valuable for our clients and cooperation partners.

Selected Milestones in 2018

- Charge carrier lifetimes of TOPCon-passivated samples reach a record value of 225 ms.
- Profound analysis of the transport mechanism of charge carriers in passivated contacts.
- Great improvement of the bottom cell of a III-V/Si multi-junction solar cell with passivated contacts and advanced light trapping enables a record efficiency value of 33.3 %.

1 *Wafer in a furnace in PV-TEC at Fraunhofer ISE.*

www.ise.fraunhofer.de/silicon-photovoltaics

Contacts

Silicon Photovoltaics
Prof. Stefan Glunz, Dr. Ralf Preu
Phone +49 761 4588-0 | sipv@ise.fraunhofer.de

Feedstock, Crystallization and Wafering
Dr. Stephan Riepe | Phone +49 761 4588-5636
sipv.material@ise.fraunhofer.de

Epitaxy, Si Films and SiC Deposition
Dr. Stefan Janz | Phone+49 761 4588-5261
sipv.csi-thinfilm@ise.fraunhofer.de

Characterization of Processing Materials and Silicon Materials
Dr. Martin Schubert | Phone +49 761 4588-5660
sipv.characterization@ise.fraunhofer.de

Doping and Diffusion
Dr. Jan Benick | Phone +49 761 4588-5020
sipv.doping@ise.fraunhofer.de

Surfaces: Conditioning, Passivation, Light-Trapping
Dr. Jochen Rentsch | Phone +49 761 4588-5199
sipv.surface@ise.fraunhofer.de

Contacting and Patterning
Dr. Markus Glatthaar | Phone +49 761 4588-5918
sipv.contact@ise.fraunhofer.de

High-Efficiency Solar Cell Fabrication and Analysis
Dr. Martin Hermle | Phone +49 761 4588-5265
sipv.hieta@ise.fraunhofer.de

Pilot Processing of Industrially Relevant Solar Cells
Dr. Florian Clement | Phone +49 761 4588-5050
sipv.pilot@ise.fraunhofer.de

Metrology and Production Control
Dr. Stefan Rein | Phone +49 761 4588-5271
sipv.metrology@ise.fraunhofer.de

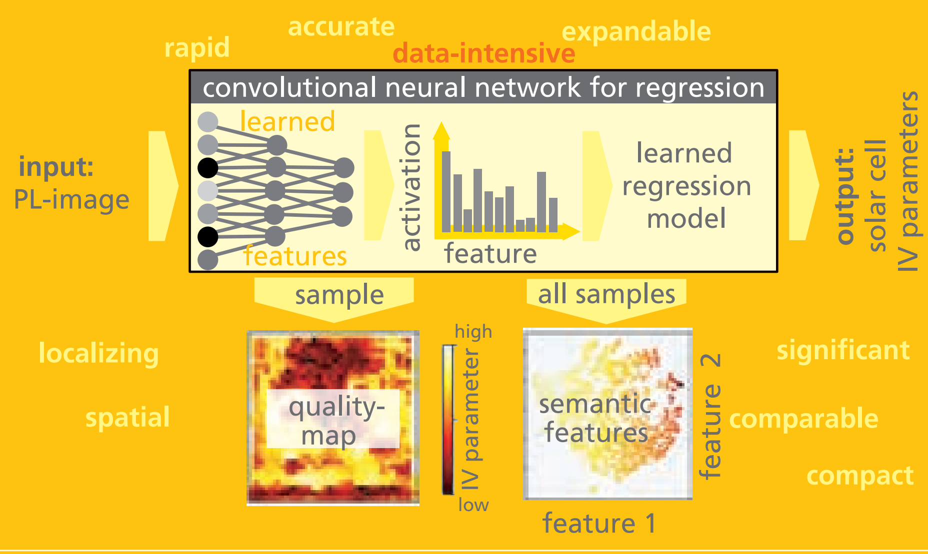
Thin-Film Silicon Solar Cells
Dr. Dietmar Borchert | Phone +49 209 15539-13
sipv.si-thinfilm@ise.fraunhofer.de

Technology Assessment
Dr. Ralf Preu | Phone +49 761 4588-5260
sipv.assessment@ise.fraunhofer.de

Selected Projects in 2018

- Rock-Star – Evaluation and Development of Rotary Printing Methods for the Manufacture of Si Solar Cells
- FINALE – Development of Industrial Printing Processes for the Production of Ultra-Fine Line Contacts for Highly Efficient Silicon Solar Cells
- INNOMET – Development of Innovative Printing Technologies for Fine Line Metallization of Si Solar Cells
- ATAKAMA – Alternative Contacting Processes and Contact Materials for Highly Efficient Silicon Solar Cells with Passivated Contacts

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



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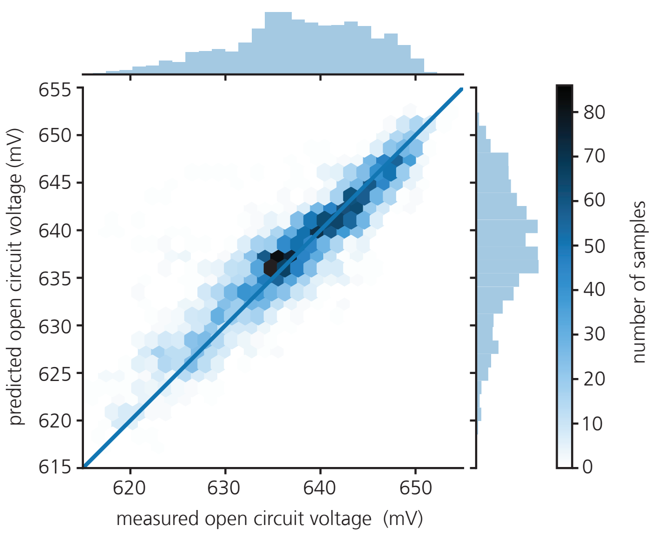
Machine Learning for Materials Evaluation in PV Production

Dr. Matthias Demant | Phone +49 761 4588-5651 | sipv.characterization@ise.fraunhofer.de

New technology in machine learning first surpassed human performance in classifying objects in 2012. As the capacity of production lines increases, purely data-based procedures for production control are gaining in importance, which can be implemented very efficiently with this technology. As part of its digitalization initiative, Fraunhofer ISE is addressing the transfer of deep learning procedures to various links of the PV value chain. To evaluate multicrystalline silicon wafers, a sufficiently broad range of data was gathered in the "Q-Wafer"[A] and "Q-Crystal"[B] projects to allow the expected solar cell quality to be predicted already from inline measurements before solar cell production. In addition to predicting the efficiency accurately with a mean error of $0.12\%_{abs}$, the process offers further advantages: In our application example, a convolutional neural network learns the direct connection between the 2D photoluminescence images of the wafer and the current-voltage parameters of the solar cell. No human specifications were needed to evaluate the input images. The model can be easily extended with additional processing and input parameters and prediction requires only a few milliseconds. Correct prediction for wafers from unknown bricks demonstrates the high degree of generalizability, so that deviations between predicted and measured efficiency can be used as indicators for processing errors and material anomalies, which can be specified by reference methods such as "modulum" that are available at Fraunhofer ISE.



Graph: Prediction of the open circuit voltage on the basis of photoluminescence images of the wafer, obtained by applying a convolutional neural network.

1 *Direct processing of the photoluminescence (PL) image of a multicrystalline Si wafer to predict the current-voltage (IV) parameters of the solar cell by application of a convolutional neural network.*

A further advantage is the quality map which can be derived from the spatially resolved activation of the network. It reveals how the network evaluates the structures in the input data. This allows causes of the evaluation result to be identified and localized. Fraunhofer ISE thus sheds light on the "black box" neural network.

A further aspect is concealed in the learned representation of the data in the depths of the network. It compresses the input data, so that efficiency-limiting patterns in the imaging data can be quantified. The data can be compared with each other on the basis of this informative representation. We see what the network has learned from the data. The semantic representation itself is used to save the image data efficiently. Crystallization can be evaluated by comparing the semantic representations of different crystals. Fluctuations in the solar-cell manufacturing process can also be investigated more specifically with the help of the extracted material properties.

[A] Supported by the German Federal Ministry for Education and Research (BMBF)
[B] Supported by the German Federal Ministry for Economic Affairs and Energy (BMWi)

Epitaxially Grown Silicon Wafers for Highest-Efficiency Solar Cells

Dr. Stefan Janz | Phone +49 761 4588-5261 | sipv.csi-thinfilm@ise.fraunhofer.de

Cost reduction and simultaneous fulfilment of the highest quality standards are the two most important guiding principles in current PV research and development. Fraunhofer ISE thus initiated a technology already several years ago which significantly reduces the production costs of high-quality silicon wafers by efficient usage of pure silicon and a low energy consumption.

This is achieved by epitaxial growth of silicon directly from chlorosilanes and recycling of a crystallization template. A stack of macro-porous layers is created within a silicon wafer by electrochemical etching. In the next step, this layer stack is thermally restructured, such that a monocrystalline template for epitaxial growth with a pre-defined fracture plane is created. This process is called "reorganization". The silicon monocrystal is then deposited layer by layer by atmospheric-pressure epitaxy. Both the thickness and the dopant concentration in the layer can be adapted during the growth process. After the growth process and a mechanical processing step, the monocrystalline layer is separated from the mother substrate and the obtained wafer (EpiWafer) is post-processed ready for further processing. The mother substrate is also treated chemically, reintroduced into the production process and used for the next cycle.

The EpiWafer can hardly be distinguished from a "conventional" monocrystalline Si wafer and can be further processed without adaptation of the subsequent processing steps to manufacture a solar cell. Furthermore, the EpiWafer can offer additional value due to the incorporation of dopant profiles and the free choice of thickness for the epitaxially grown layers. Thus, possible further developments of the EpiWafer technology include replacement of solar cell processes such as emitter diffusion or the manufacturing of flexible silicon films.

The two core processes of this EpiWafer technology are the electrochemical etching of silicon and the epitaxy of silicon at atmospheric pressure. Although these processes have been successfully applied already for many years in the semiconductor industry, industrial equipment with high throughput for these processes was not available. Fraunhofer ISE has closed this gap and a spin-off called NexWafe was founded in 2015 on the basis of the existing know-how. In very close cooperation, research and development has focussed on continuous improvement in the quality and yield of the processes. As a result of these joint efforts, the technology has now achieved production readiness.

1 *Pilot facility developed at Fraunhofer ISE for the continuous thermal reorganization of porous layers and epitaxy of silicon (ProConCVD).*

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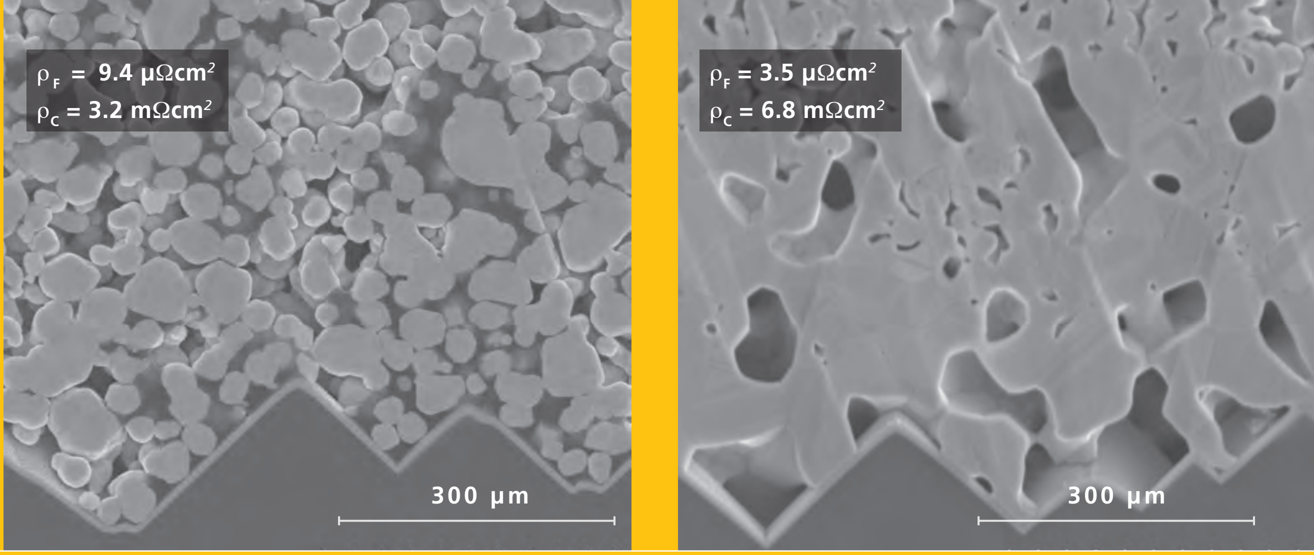


Passivating Contacts – A Future Key Technology

Frank Feldmann | Phone +49 761 4588-5287 | sipv.contact@ise.fraunhofer.de

PV module power has increased continuously over recent years due to the introduction of PERC technology to industrial solar cell production. In PERC technology, the dominating losses at the metal-semiconductor contacts are tackled by reducing the contact area and applying dielectric back-surface passivation. Passivating contacts do not require any local structuring, as they passivate the surface excellently and simultaneously make low contact resistance feasible. As a result, very high efficiency values can be achieved with leaner production technology.

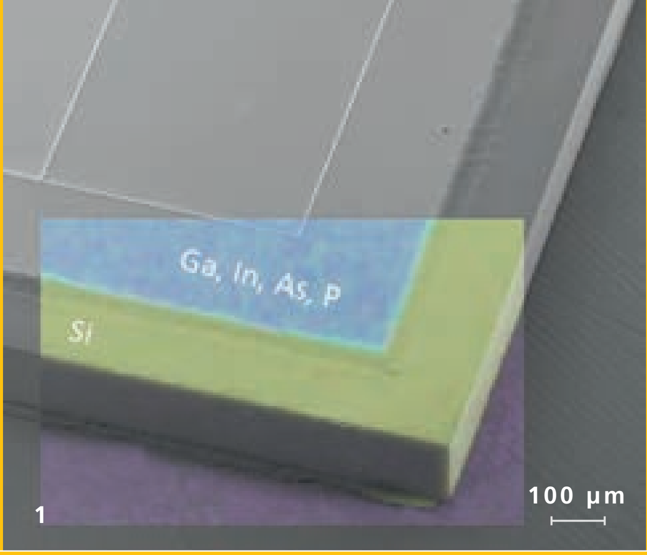
In addition to heterojunction technology (HJT), research has been conducted at Fraunhofer ISE for several years on passivating contacts based on polycrystalline silicon (TOPCon). The great potential of this technology has already been demonstrated with prototype solar cells, which attain efficiency values of up to 25.8 %. Current research work is focussing on:

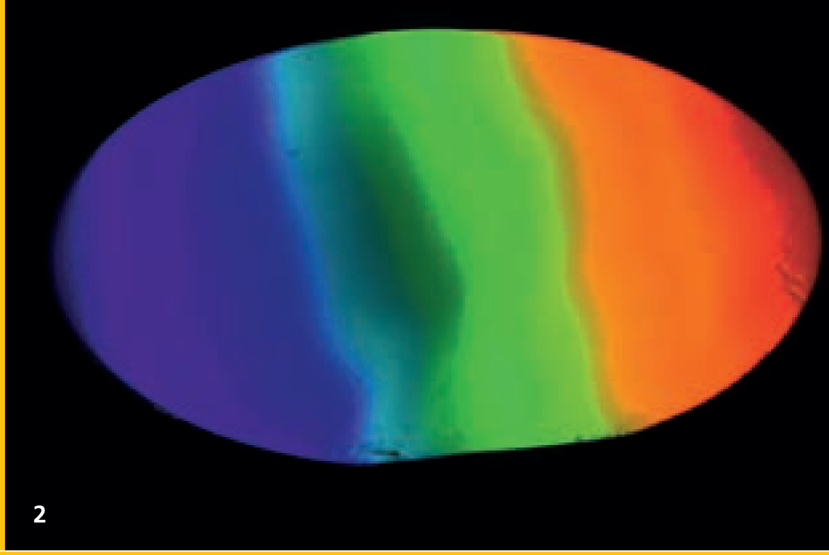
- development of deposition processes with high-throughput equipment
- inexpensive metallization processes
- integration into solar cells and modules

In addition to the LPCVD deposition processes that are established in the semiconductor branch for polycrystalline silicon, we are also evaluating PECVD processes in cooperation with European equipment manufacturers. We successfully demonstrated that the TOPCon technology developed at Fraunhofer ISE can also be implemented with this type of equipment.

In comparison to heterojunction technology, the greater temperature stability of passivation is an advantage of TOPCon technology. Thus, a transparent conductive oxide (TCO) can be deposited at higher temperatures than is usual for HJT, for example. As a result, better layer properties can be achieved. Furthermore, the higher processing temperatures improve the conductivity of the metal pastes. The reduction in material consumption leads on to a cost reduction. Fig. 1 shows the positive influence of a higher processing temperature on the microstructure of the low-temperature paste as an example. Sintering the metal fingers at temperatures above 300 °C leads to reduction of the specific finger resistance ρ_F, which is in the same range as that achieved with high-temperature pastes after a typical firing process. In addition, analysis showed that low specific contact resistances at the metal/TCO interface are simultaneously possible.

1 *SEM images of a low-temperature silver paste after thermal curing at 200 °C (left) and 350 °C (right).*





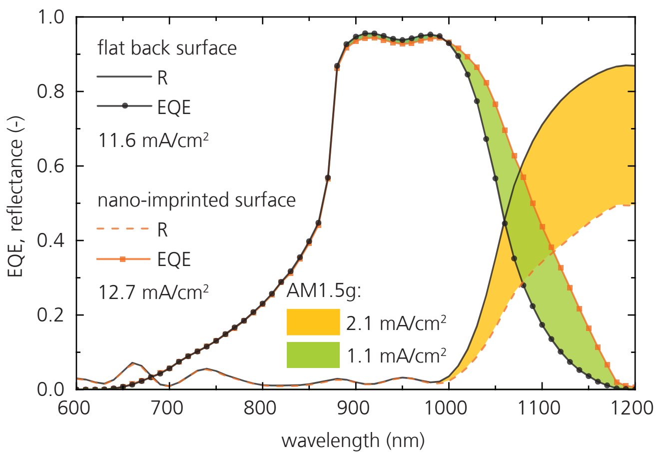
Optimized Bottom Cells for Silicon-Based Multi-Junction Solar Cells

Dr. Jan Christoph Goldschmidt | Phone +49 761 4588-5475 | emergingpv.silicon@ise.fraunhofer.de

Most of the solar electricity generated around the world is obtained with single-junction silicon solar cells. The next generation could be multi-junction solar cells, as better use of the solar spectrum can be made with this technology. Silicon is also excellently suited for this application – due to its band gap, its low price and because it is already established in the photovoltaic industry. For these reasons, at Fraunhofer ISE we are working at Fraunhofer ISE on optimizing silicon solar cells as the bottom cell and substrate material for application in multi-junction solar cells, e. g. in combination with thin top cells of III-V compound semiconductors or perovskites.

A direct connection between the silicon bottom solar cell and a top cell to form a single multi-junction solar cell with only two electric contacts is advantageous for integration into modules. However, this concept demands a transparent electric contact between the silicon and the top sub-cell. In addition, the silicon surface must be passivated. With the Tunnel Oxide Passivated Contacts (TOPCon) that were developed at Fraunhofer ISE, a new technology is available which meets both criteria particularly well. At the cell level, we have already demonstrated a contribution of 690 mV by the TOPCon silicon solar cell to the total open-circuit voltage of a multi-junction solar cell. An excellent contact between the silicon and top sub-cells was created by direct wafer bonding, but other, less expensive technologies such as application of conductive adhesives have also proven to be promising.

In order to improve light trapping by the silicon bottom cell further, we have developed optical structures for the back surface of the cell. These structures are made by nano-imprint lithography and lengthen the light path through the silicon solar cell by scattering and/or diffraction, increasing absorption. For example, we significantly increased the short-circuit current density of the silicon bottom cell (from 11.6 to 12.7 mA/cm² in a triple solar cell, see graph) with a crossed metal grating. The light trapping due to these optical structures is of similar quality to that due to the common front-surface structures with pyramids. The successful integration of TOPCon technology and photonic back-surface gratings enabled the preparation of a 2-terminal multi-junction solar cell that currently holds the world record with an efficiency value of 33.3 %.

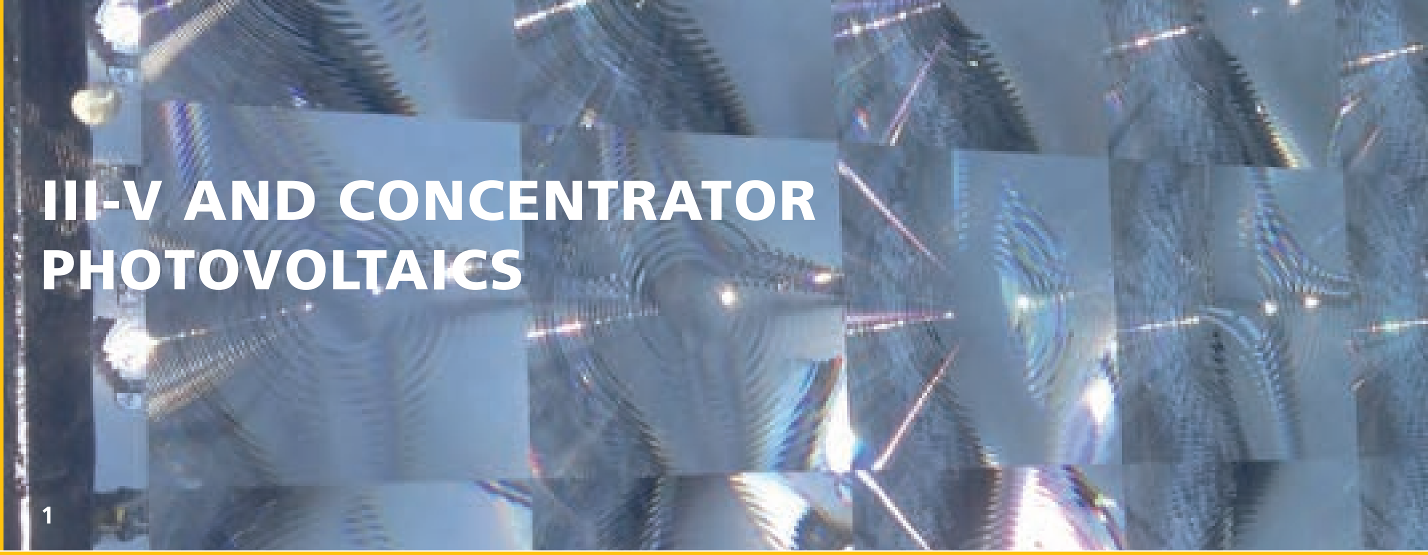


Graph: Influence of the back-surface grating (nano-imprint) on the reflectance of the multi-junction solar cell and the quantum efficiency of the silicon bottom cell.

1 *Electron micrograph of the multi-junction solar cell. X-ray spectroscopy identifies the elements of the top cell (gallium, indium, arsenic, phosphorus) and the bottom cell (silicon).*

2 *The structuring created by nano-imprinting of the back surface of the solar cell refracts the incident light and splits it spectrally into different colors.*

III-V AND CONCENTRATOR PHOTOVOLTAICS



52
Total staff

21
Journal articles and contributions to books

24
Lectures and conference papers

5
Newly granted patents

In this topic, Fraunhofer ISE addresses the demands of space and concentrator photovoltaics. In addition, we work on efficient conversion of light from other 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 mm² and 1 cm², which operate at very high solar radiation intensity. 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, optoelectronic packaging 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 heat and power, desalination of seawater or direct production of solar hydrogen. We achieve innovations by system-relevant conception and set ourselves the goal of providing the best solutions in the world for our clients. In doing so, we can draw on modern, industrially relevant infrastructure and many years of expertise at the Institute.

Selected Milestones in 2018

- New world record: CPV sub-module (122 cm²) with aspherical glass lenses and four-junction solar cells of the next generation achieves a CSTC efficiency value of 41.4 % (39.5 % CSOC).
- Six FLATCON® concentrator modules produced with an area of 1089 cm². The efficiency value with commercial solar cells and lenses is 35.1 % CSTC (33.0 % CSOC).
- With a new "EyeCon" concentrator module, we convert both direct and diffuse radiation into electricity for the first time and measure efficiency values of up to 36.8 % in Freiburg with reference to the global normal irradiance.
- We achieve high data transfer rates of 0.5 Gb/s (3 dB bandwidth, 24.5 MHz) with our GaAs photovoltaic cells and monochromatic efficiency values of up to 67 %.
- Directly grown III-V/ Si multi-junction solar cell achieves an efficiency value of 22 % for the first time under AM 1.5g conditions.

1 *FLATCON® concentrator module.*

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

Contacts

III-V and Concentrator Photovoltaics
Dr. Frank Dimroth | Phone +49 761 4588-5258
cpv@ise.fraunhofer.de

III-V Epitaxy and Solar Cells
Dr. David Lackner | Phone +49 761 4588-5332
cpv.III-V@ise.fraunhofer.de

Concentrator Assemblies
Maike Wiesenfarth | Phone +49 761 4588-5470
cpv.assemblies@ise.fraunhofer.de

Concentrator Optics
Dr. Peter Nitz | Phone +49 761 4588-5410
cpv.optics@ise.fraunhofer.de

High-Concentration Systems (HCPV)
Maike Wiesenfarth | Phone +49 761 4588-5470
cpv.highconcentration@ise.fraunhofer.de

Low-Concentration Systems (LCPV)
Maike Wiesenfarth | Phone +49 761 4588-5470
cpv.lowconcentration@ise.fraunhofer.de

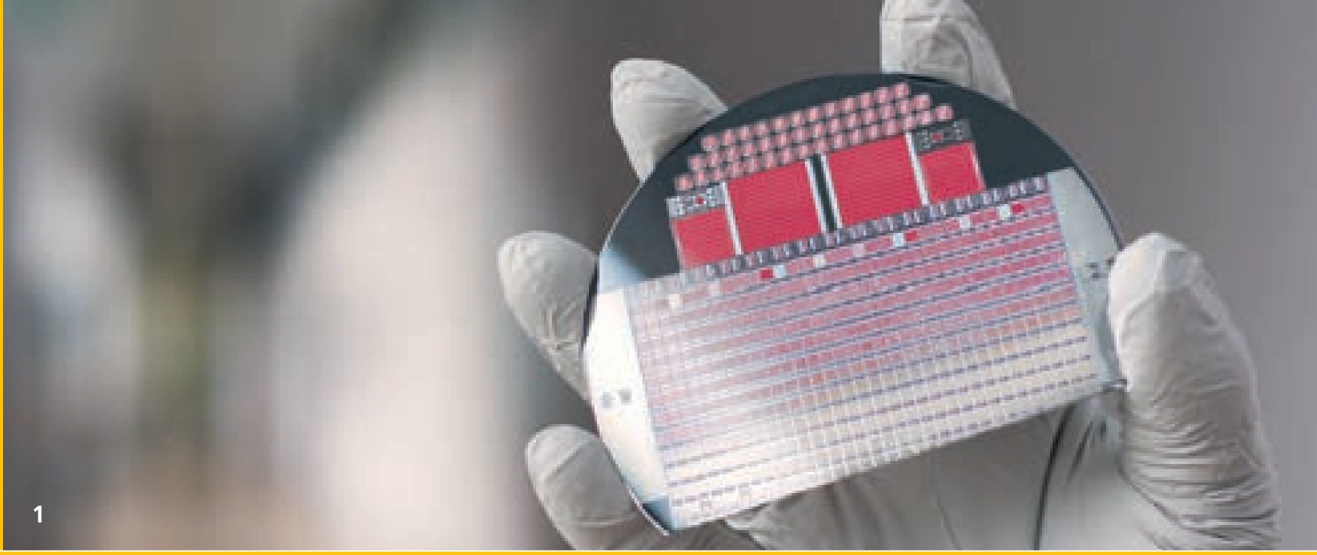
Silicon Concentrator Solar Cells
Dr. Florian Clement | Phone +49 761 4588-5050
cpv.silicon@ise.fraunhofer.de

Power-by-Light
Dr. Henning Helmers | Phone +49 761 4588-5094
power.by.light@ise.fraunhofer.de

Selected Projects in 2018

- LightBridge – Electronic System for the Wireless Power Supply of a Subretinal Micro Implant
- HeKMod4 – Highly Efficient Concentrator Module with GaSb-Based Four-Junction Solar Cell
- CPVMatch – Cutting-Edge Technologies and Cells for Concentrator Photovoltaic Modules Enable Highest Efficiencies
- CPVMod – CPV Module in Modular Design; Sub-Project: Module Design and Performance

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



III-V-Based Photovoltaics for the "Internet of Things (IoT)" and Indoor Spaces

Dr. Henning Helmers | Phone +49 761 4588-5094 | power.by.light@ise.fraunhofer.de

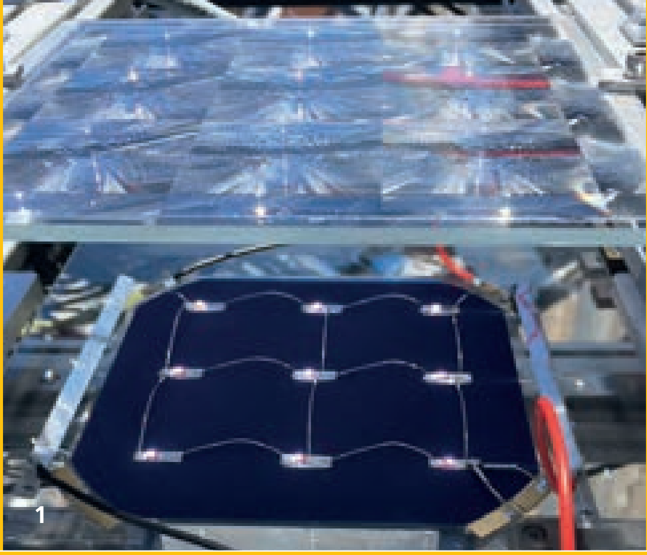
In our increasingly digitalized and interconnected world, the "Internet of Things (IoT)" is becoming more and more important. New applications are rapidly arising here for consumers, commerce, industry, infrastructure and the energy system. In most of these applications, there is a call for small and wireless devices with integrated sensors, which can simply be positioned anywhere. Two decisive factors in the development of such devices are the implementation of bi-directional communications and the power supply. Autonomous solutions for the latter task are interesting to enable truly self-sufficient operation without an external supply of energy. This means that neither cables nor batteries and their maintenance are needed. Alternatively, a wireless optical power supply that converts light from an external source can be implemented (Power-by-Light).

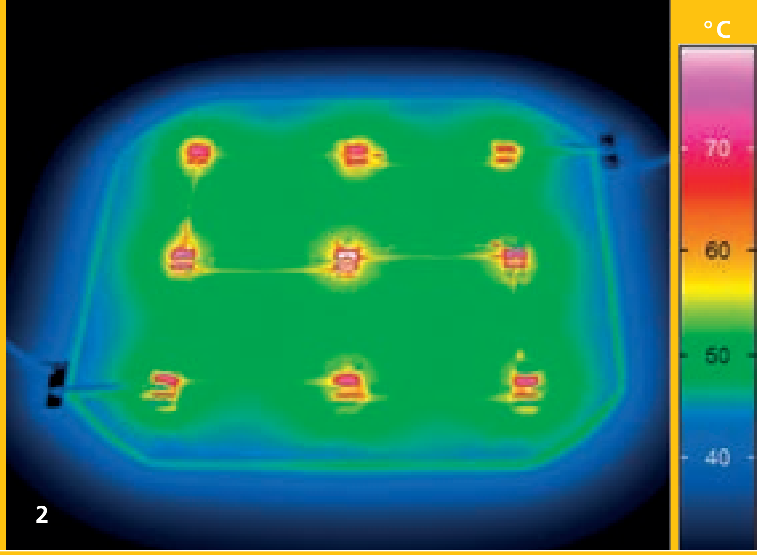
We are addressing these topics at Fraunhofer ISE with III-V-based photovoltaic cells. Photovoltaic cells based on gallium indium phosphide have material properties which suit them well for conversion of indoor light. Their absorption behavior ideally suits the emission spectra of artificial light sources (white LED sources and fluorescent lamps), and the solar cells feature excellent low-light behavior due to the high material quality. In initial measurements with a 1 cm^2 cell, we achieved an efficiency value of 15.5 % under low light conditions (1.7 W/m^2 corresponds to about 210 lux).

For applications in the "Internet of Things (IoT)", we are also working on technology which allows a power supply and data communication to be integrated into a single component. This makes compact designs feasible and saves costs. For simultaneous optical wireless information and power-transfer (SWIPT), Fraunhofer ISE developed a gallium arsenide-based photovoltaic cell. With the support of the University of Edinburgh we have recorded a peak data rate of 0.5 % Gb/s (3dB bandwidth: 24.5 MHz). Under monochromatic illumination this cell was characterized by an efficiency value of 42 % (847 nm, 0.46 W/cm^2). A comparable cell, which was prepared by thin-film technology with a back-surface mirror, featured a peak monochromatic efficiency value of 67 % (860 nm, 10 W/cm^2).

In addition to highly efficient conversion of the incident light (photovoltaic cell) and fast data reception (photodiode) we are currently working on the option of using the same cell also as a light-emitting data transmitter (LED). Efficient light extraction is achieved by the high radiative efficiency (Fig. 1) of the III-V materials.

1 *Photovoltaic cells can also be used as data transmitters: GaInP-based cells on a wafer emit red light (To demonstrate the effect, the flash light of the camera was used as the excitation source).*





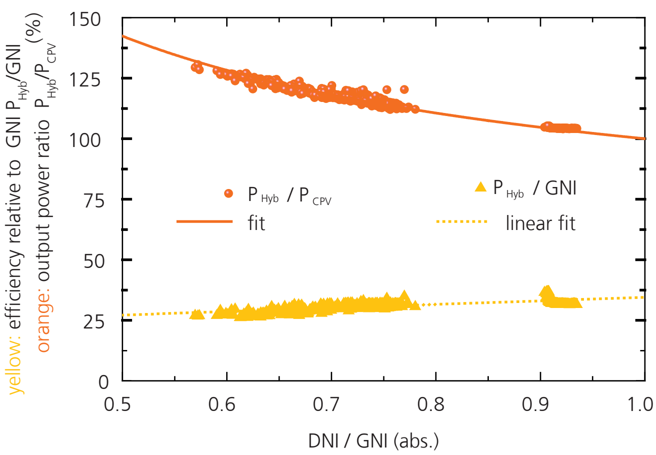
EyeCon Concentrator: Electricity from Direct and Diffuse Sunlight

Maike Wiesenfarth | Phone +49 761 4588-5470 | cpv.highconcentration@ise.fraunhofer.de

Concentrator photovoltaic modules (CPV), which are based on III-V multi-junction solar cells, achieve the highest efficiency of all PV technologies. In earlier work at Fraunhofer ISE, already 36.7 % of the incident direct solar radiation was converted into electricity by the FLATCON® module under concentrator standard test conditions. These CPV modules follow the sun with a two-axis tracker unit in order to focus the direct light within the small acceptance angle of the optics (< 1°) onto the cell. This also increases the annual energy yield significantly. However, if the sun does not shine directly onto the module, no electricity is generated. To change this situation, Fraunhofer ISE developed "EyeCon", an innovative CPV hybrid module. The module concept consists of III-V multi-junction solar cells, which are mounted on silicon solar cells. The high-efficiency multi-junction solar cell converts concentrated, direct solar radiation into electricity, whereas the silicon solar cell absorbs both the diffuse and the scattered sunlight. This hybrid configuration increases the power density and allows application at locations with a higher share of diffuse radiation. As the silicon solar cell can be used simultaneously for heat distribution, thereby replacing the metal substrate used for the heat dissipation from the CPV cells; the cost increase is small.

We have confirmed the benefit of the heat distribution by finite-element simulation, images with infrared thermography and outdoor measurements (Fig. 2). The investigations demonstrate that it is possible to keep the temperature of the concentrator solar cell below 70 °C (under concentrator standard operating conditions with heat input of 1.25 W at a concentration of 226x). In this case, that is only 13 K warmer than in a module with a conventional copper substrate as the heat distributor.

Prototype modules – consisting of our high-efficiency four-junction solar cells (Ø = 3 mm), mounted on a back-contacted silicon solar cell (12.5 x 12.5 cm²) with a 3 x 3 array of Fresnel lenses (each 4 x 4 cm²) – achieved a maximum efficiency of 36.8 %. The value is with reference to the global normal irradiance GNI; at the time of the measurement, the ratio of direct to global normal irradiance (DNI/GNI) was 0.91 (see graph). For DNI/GNI ratios of 0.6 in Freiburg, the EyeCon module generates up to 25 % additional electricity by the conversion of diffuse light in the silicon solar cell. This demonstrates the high potential of this development approach to increase the annual solar energy yield in countries like Germany.

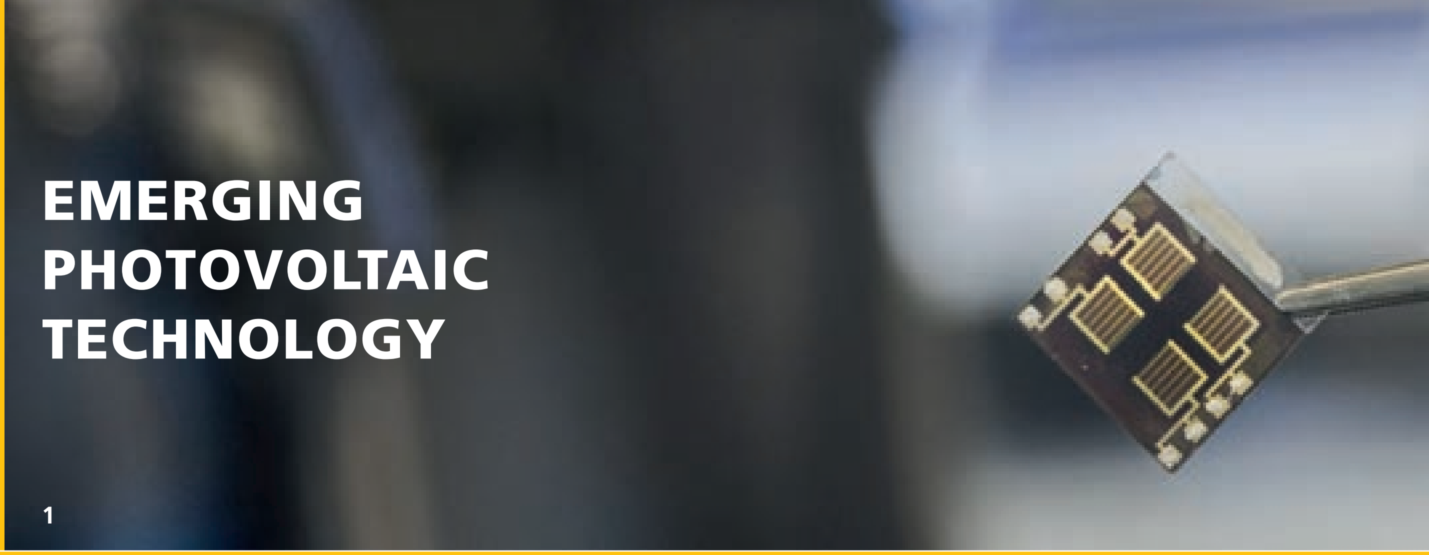


1 *EyeCon prototype module with 9 CPV cells mounted on a Si solar cell with an area of 125 x 125 mm².*

2 *Infrared thermograph for a heat input into the CPV cells of 1.37 W.*

Graph: Conversion efficiency relative to the global normal irradiance GNI (yellow) and ratio of the power from the hybrid module to that of a standard CPV module (orange) as a function of the ratio of direct to global normal irradiance.

EMERGING PHOTOVOLTAIC TECHNOLOGY



36
Total staff

21
Journal articles and contributions to books

15
Lectures and conference papers

3
Newly granted patents

Emerging Photovoltaic Technology 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 levelized cost of electricity. This includes improving the efficiency of well-established solar cells, e. g. of crystalline silicon, by improving the absorptive and reflective properties with 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 a tandem concept that is multi-junction 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.

1 *Glass substrate with four semi-transparent perovskite solar cells, produced at Fraunhofer ISE.*

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

Contacts

Emerging Photovoltaic Technology
Dr. Uli Würfel | Phone +49 761 203-4796
emergingpv@ise.fraunhofer.de

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

Organic and Perovskite Solar Cells
Dr. Uli Würfel | Phone +49 761 203-4796
emergingpv.organic@ise.fraunhofer.de

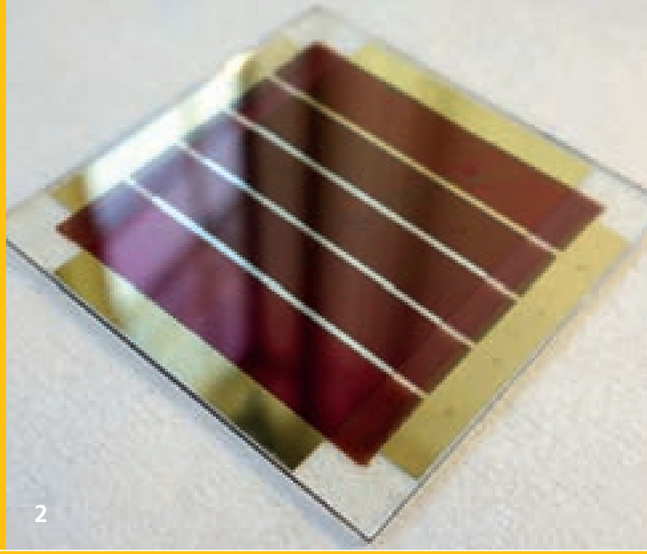
Photon Management
Dr. Jan Christoph Goldschmidt | Phone +49 761 4588-5475
emergingpv.photonics@ise.fraunhofer.de

Tandem Solar Cells on Crystalline Silicon
Dr. Stefan Janz | Phone +49 761 4588-5261
emergingpv.silicon@ise.fraunhofer.de

Selected Projects in 2018

- ESPResSo – Efficient Structures and Processes for Reliable Perovskite Solar Modules
- APOLO – SmArt Designed Full Printed Flexible RObust Efficient Organic HaLide PerOvskite solar cells

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



Organic Photovoltaics for the "Internet of Things"

Dr. Uli Würfel | Phone +49 761 203-4796 |
emergingpv.organic@ise.fraunhofer.de

Digitalization, Industry 4.0 and particularly the "Internet of Things" (IoT) count as significant growth markets. It is expected that in 2020, two-digit billions of "Things", i. e. sensors as well as general devices and components of consumer electronics, will be connected with each other via the Internet. These all have to be supplied with energy at the lowest possible cost. This can be done by "energy harvesting", among other approaches. Small amounts of energy from movement or heat are gathered, or primarily photovoltaic energy conversion of ambient lighting is applied. As many sensors and small electronic components are used inside buildings, solar cells that are responsible for their power supply must operate at very low illuminance values. In addition, typical indoor illumination spectra differ significantly from the solar spectra, as they have been optimized for the human eye. Here, organic photovoltaics offers an advantage. The absorptance spectrum of organic absorbers is very well suited for indoor applications, due to its significantly larger band gap compared to crystalline silicon. In addition, they can be deliberately adapted to the surrounding conditions by synthesis of appropriate materials. Last but not least, it is very simple to integrate the thin OPV films into the required objects. Fraunhofer ISE has many years of experience in researching the necessary physical and technological questions. We also develop industrially relevant cell and module concepts. By applying our electric models, we can optimize module structures especially for the "Internet of Things (IoT)".

1 *Flexible organic solar cell module in a configuration that allows a high area-utilization potential of 87 %.*

Doctor-Blade Coating of Planar Perovskite Solar Cells and Mini-Modules

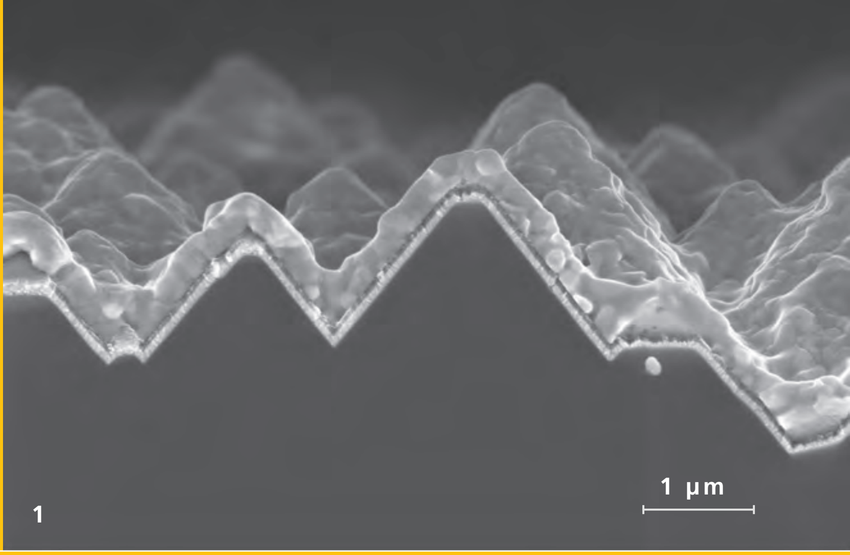
Dr. Uli Würfel | Phone +49 761 203-4796 |
emergingpv@ise.fraunhofer.de

Perovskite solar cells are usually produced on small areas by spin coating. Although this works well, the method is not suitable for up-scaling to large areas. Fraunhofer ISE has therefore investigated approaches in which the perovskite absorber is deposited by doctor-blade coating. It became evident that the quality of the layers, and thus also the efficiency value of the solar cells prepared from them, depended decisively on the drying dynamics. We compared samples which we exposed to a nitrogen stream for drying with others which had not been subjected to this process. X-ray diffractometry revealed that the directed stream of nitrogen resulted in more order within the multicrystalline perovskite layer, which also caused more photoluminescence from the samples that had been treated in that way.

In the solar cells with a so-called "p-i-n architecture" with PEDOT:PSS (poly-3,4-ethylene dioxythiophene) as the hole transport layer, the higher degree of order in the absorber layer resulted in higher values for the conversion efficiency. An efficiency value of up to 11.8 % was reached on an active area of 1.1 cm^2. This value was increased to 12.4 % by applying sputtered NiO_x as the hole transport layer.

Initial mini-modules of three solar cells connected in series with an active area of 5.9 cm^2 and PEDOT:PSS as the hole transport layer showed a promising result with an efficiency value of 9.7 %.

2 *Perovskite solar module made of three serially connected cells that had been prepared by doctor-blade coating.*



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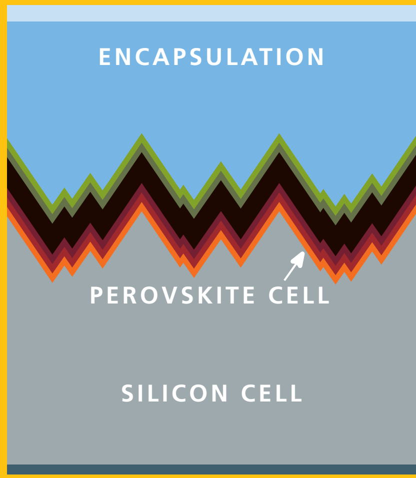


2

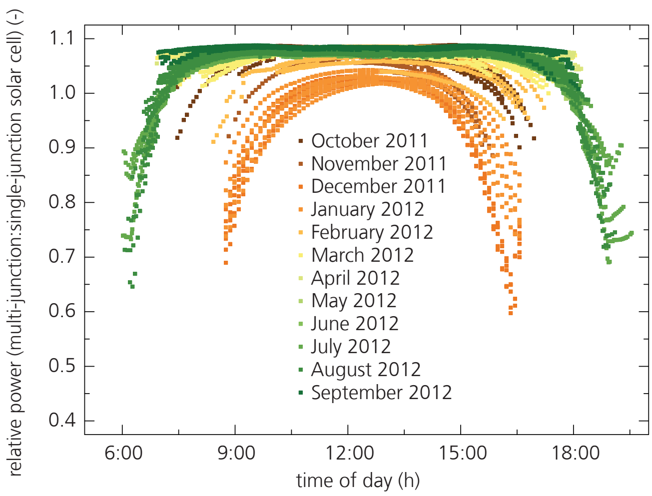
From the Tandem Record Cell to Yield Analysis

Nico Tucher | Phone +49 761 4588-2638 | emergingpv.silicon@ise.fraunhofer.de

An impressive record efficiency value of 33.3 % for a silicon-based multi-junction solar cell was achieved at Fraunhofer ISE with a III-V-on-silicon tandem solar cell. But how does this type of cell perform at the module level? And what is the energy yield of modules with multi-junction solar cells in comparison to single-junction solar cells, if a complete year and the solar radiation at a specific location is taken into account? These questions are also very important for the emerging perovskite-on-silicon tandem solar cells.

In a simulation-based approach to answer these questions, the "OPTOS" and "YieldOpt" tools that had been developed at Fraunhofer ISE were connected with each other. "OPTOS" allows tandem solar cells with an arbitrary number of layers and different surface structures to be optically modelled efficiently at the cell and module level. Important decisions concerning the selection of materials or structure parameters can already be made and optimized on this basis. The spectrally resolved absorptance that is calculated with "OPTOS" is also an important component for further analysis with "YieldOpt". This tool connects the optical and electrical simulation of the solar cell with the incident solar spectrum that is determined by measurement or simulation. In this way, different solar cell concepts can be modelled under realistic conditions and their yield in the field can be estimated and compared.

To date, the models have resulted in identification of three important results. Optimization of the back-surface structure has a great potential to increase the record efficiency for III-V-on-silicon tandem solar cells to even higher values. In addition, front-surface textures reduce the reflection losses for perovskite-on-silicon tandem solar cells significantly at the cell and module level, providing confirmation of the approach already being followed, to evaporate perovskite layers onto textured silicon cells. Furthermore, both III-V-on-silicon and perovskite-on-silicon tandem solar cells can clearly increase the yield for different locations and radiation conditions when compared to single-junction silicon solar cells.

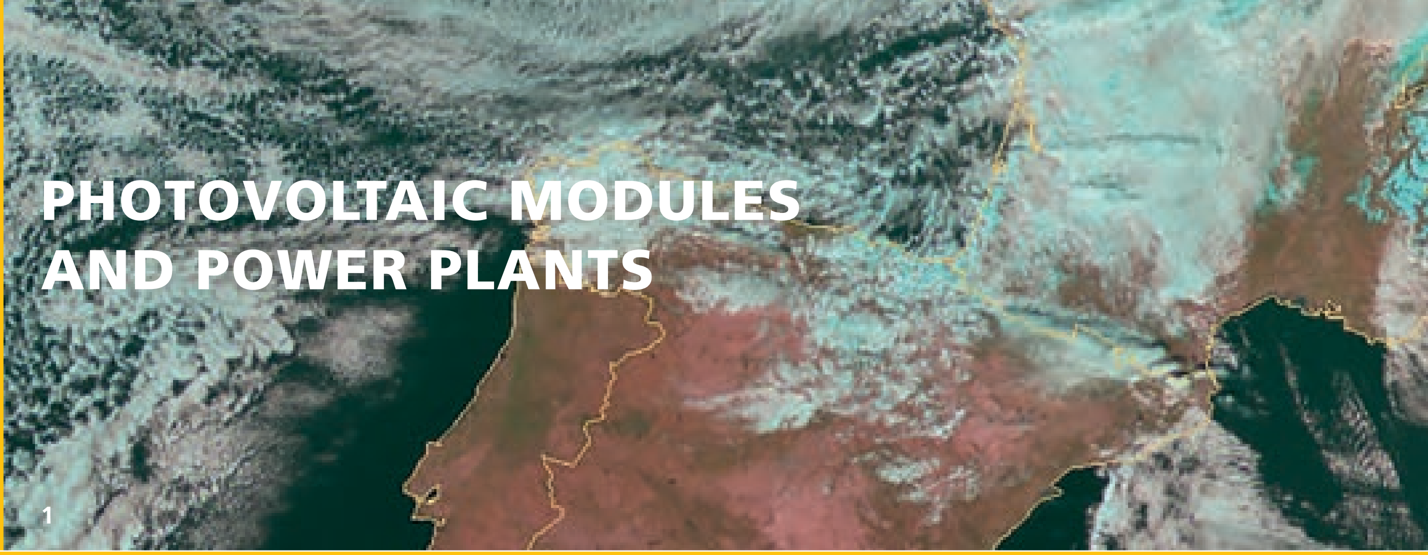


Graph: Power output of an encapsulated perovskite-on-silicon tandem solar cell relative to that of a single-junction silicon cell over a year, presented for different times of day.

1 *SEM image of a perovskite layer – conformally deposited onto a random pyramid surface of a monocrystalline silicon wafer.*

2 *Schematic drawing of an encapsulated perovskite-on-silicon solar cell.*

PHOTOVOLTAIC MODULES AND POWER PLANTS



123
Total staff

9
Journal articles and contributions to books

34
Lectures and conference papers

2
Newly granted patents

Module technology transforms solar cells into durable products for safe operation in PV power plants. The Module-TEC – Photovoltaic Module Technology Center is equipped with a wide range of modern processing and analytical platforms for connecting and laminating solar cells, especially for materials testing, and developing products and processes. We apply measurement and simulation to analyze cell-to-module ratios (CTM) and offer licences for the "SmartCalc CTM" calculation tool.

The reliability of modules is tested in our accredited TestLab PV Modules for certification according to international standards 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 only 1.3 % for crystalline modules.

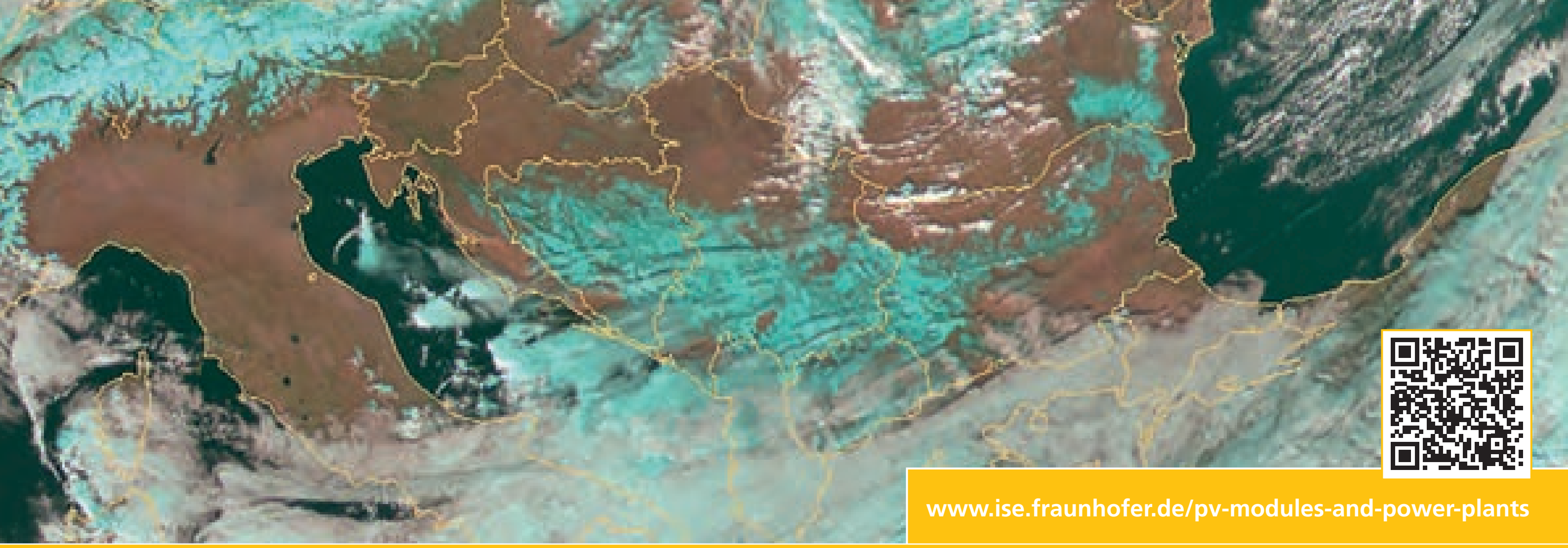
For PV power plants, we offer comprehensive quality control in all project phases up to continuous operation. We take site-specific and climatic factors into account to prepare accurate yield predictions and provide advice on the project-specific selection of high-quality components. We develop reliable, probabilistic methods to forecast the performance of PV systems and provide real-time irradiance data for predictions of PV electricity generation and the monitoring 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.

Selected Milestones in 2018

- Successful commissioning of the first industrial stringer applying conductive adhesives to connect solar cells in Module-TEC; production of an adhesive-based 320 W module with 60 heterojunction cells.
- New production concept for building-integrated solar modules reduces production costs for individually adapted modules in series production.
- Clear increase in the efficiency of bifacial shingle modules: Compared to conventional modules, the efficiency is about 30 $\%_{rel}$ higher.
- Development of a global load classification system for solar materials to categorize high loads e. g. due to UV radiation, corrosion and humidity.

1 *Satellite data enable prompt, highly resolved images of the solar irradiance and generated photovoltaic electricity, as well as the prediction of PV electricity yields up to several hours in advance.*



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

Contacts

Photovoltaic Modules and Power Plants
Dr. Harry Wirth | Phone +49 761 4588-5858
pvmod@ise.fraunhofer.de

Module Technology
Dr. Holger Neuhaus | Phone +49 761 4588-5825
pvmod.tech@ise.fraunhofer.de

Module Calibration
Frank Neuberger | Phone +49 761 4588-5280
pvmod.callab@ise.fraunhofer.de

Service Life and Failure Analysis
Daniel Philipp | Phone +49 761 4588-5414
pvmod.testlab@ise.fraunhofer.de

Photovoltaic Power Plants
Boris Farnung | Phone +49 761 4588-5471
pvmod.powerplant@ise.fraunhofer.de

Agro-Photovoltaics
Stephan Schindele | Phone +49 761 4588-5961
pvmod.apv@ise.fraunhofer.de

Building-Integrated Photovoltaics
Dr. Tilmann Kuhn | Phone +49 761 4588-5297
pvmod.bipv@ise.fraunhofer.de

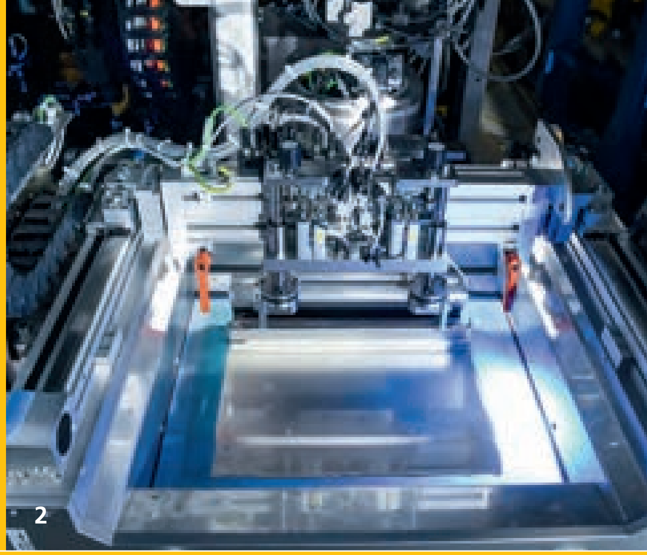
PV for Mobility
Dr. Martin Heinrich | Phone +49 761 4588-5024
pvmod.mobility@ise.fraunhofer.de

Solar Radiation and Performance Prediction
Dr. Elke Lorenz | Phone +49 761 4588-5015
pvmod.forecast@ise.fraunhofer.de

Selected Projects in 2018

- CPVMatch – Cutting-Edge Technologies and Cells for Concentrator Photovoltaic Modules Enable Highest Efficiencies
- SCOPE – Project Data Environment and Modelling of Multi-functional Building Products with Focus on the Building Envelope

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



Adhesive Bonding instead of Soldering – Gentle Connection Technology

Dr. Achim Kraft | Phone +49 761 4588-5544 | pvmod.tech@ise.fraunhofer.de

Electrically Conductive Adhesives (ECAs) have established themselves as an important alternative to soldered connections in industrial production. Together with the equipment manufacturer teamtechnik, adhesive technology for connecting solar cells was developed to market readiness in the "KleVer"[A] project. During the research project, a stringer with an adhesive processing unit was successfully taken into operation and extensively tested at Fraunhofer ISE. The stringer is capable of adhesively contacting solar cells (full or half cells) with up to five bus bars at a rate of about 1600 cells per hour. With this value, the rate in industrial production is only slightly lower than for cell soldering. Novel ECA products cure with a peel strength exceeding 1 N/mm in less than 20 s and thus enable the high throughput.

1 *Solar cell without bus bars: The conductive adhesive is printed perpendicularly to the contact fingers on the cell and allows connection with the ribbons.*

2 *Adhesive processing unit of the stringer for connecting solar cells.*

Adhesive Bonding for HJT and Shingle Modules

The significantly lower processing temperatures compared to soldering reduce thermal and mechanical stress on the sensitive solar cells. In particular, temperature-sensitive high-efficiency cells (heterojunction cells – HJT), very thin cells and shingle cells can be electrically connected with the gentle ECA process. The processing temperature for curing the adhesive remains below the critical temperature for HJT cells of 200 °C. Adhesive bonding is well suited for shingle connection of solar cells. Thermo-mechanical stresses in the PV module can be reduced by the lower stiffness of the adhesive layer. The risk of micro-cracks and fractures in the cells decreases accordingly. Unlike conventionally utilized solder, ECAs do not contain any lead. The silver fraction in the conductive adhesives was reduced significantly. In combination with an optimized application of the adhesive with screen-printing processes, we have succeeded in implementing cost-effective solutions for adhesive-based connections. The reliability of the adhesive connections was checked by climatic chamber tests and detailed analyses in the accredited TestLab PV Modules.

[A] Supported by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Maximum Yields and Greatest Reliability with Bifacial PV Modules

Dr. Christian Reise | Phone +49 761 4588-5282 | pvmod.powerplant@ise.fraunhofer.de

Bifacial PV modules convert radiation that is incident on the back surface into additional electricity. Depending on the module design, mounting and surroundings, additional yields of typically 5 to 15 % can be achieved. To allow our clients to tap this potential, we have comprehensively analyzed the specific features of bifacial technology from the solar cell up to the system.

Module Design

The higher current density requires adaptation of the cell and connector design. At Fraunhofer ISE, the "SmartCalc.CTM" calculation tool was extended to include bifacial modules. The tool allows module power and efficiency to be optimized by varying numerous material and design parameters. Module manufacturers need only a few mouse clicks to improve their product.

Characterization and Testing

In CalLab PV Modules at Fraunhofer ISE, methods were developed to characterize bifacial modules with simultaneous irradiance of both surfaces and to determine the bifaciality factor. This factor quantifies the ratio of the efficiency values for irradiance of the back to the front and is needed for product specification and yield prediction. In TestLab PV Modules, we have developed methods for testing bifacial modules and for adapting the current testing standards, IEC 61215 and IEC 61730. Particular attention was paid to the role of back-surface irradiance and partial shading during hot spot testing.

Yield Analysis and Optimization

The yield of a bifacial PV power plant depends on many different parameters. Their complex interaction can be modelled accurately with ray-tracing methods. In ray-tracing, we use an algorithm that calculates the incident light beams in three-dimensional space. In this way, we obtain much more accurate results than with widespread approximations based on view factor procedures. Our tool allows not only the analysis and optimization of the system design, e.g. the distance between module rows or the ground properties (albedo). Manufacturers also receive indications on designing modules and mounting racks to avoid critical partial shading on the back surface of the module. The yield predictions were convincingly confirmed by monitoring bifacial modules at different locations. Installation companies and investors use our predictions to present the added value of bifacial technology.

1 *Test facility at Fraunhofer ISE to calibrate bifacial PV modules.*

ENERGY TECHNOLOGIES AND SYSTEMS

Fraunhofer ISE uses this membrane distillation cell to develop water purification processes to separate out highly toxic substances. Applications include waste water or processing fluids for the galvanic industry or semiconductor production.

The energy transformation has entered its second phase, not only in Germany but also in many countries that have achieved a similarly high penetration of their energy supply by renewable energy sources. The first phase of the transformation was marked by key developments and cost reductions in the conversion of renewable energy sources, particularly wind, solar energy and biomass, to electricity. These developments meant that an affordable energy transformation towards a more efficient, sustainable, resilient and renewably based energy system was conceivable at all. Strong growth in installed capacity over past years has resulted in renewable energy sources supplying 40 % of Germany's electricity in 2018. The heat, transport and industry sectors, however, are lagging far behind. In Germany, we are still mostly heating our buildings with natural gas and heating oil. The mobility sector relies largely on fossil fuels. Therefore, holistic integration of renewable energy sources is due now – in the next phase – and with it much stronger coupling between the electricity, heat and transport sectors. Much speaks in favor of increased electrification of all 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-equipped electric vehicles. In areas where it is difficult to use electricity directly, such as heavy-freight, ship and aviation transport or also industrial processes, energy can be supplied increasingly with renewable, chemical fuels.

As biomass resources are limited, hydrogen will play an increasingly larger role here. Renewable hydrogen can be reconverted into electricity with stationary or mobile fuel cells or be used directly in industrial processes. Also, hydrogen combined with CO_2 can be further converted into renewable synthetic fuels or chemicals for industry.

Since its founding, Fraunhofer ISE has worked on many technologies and projects which are highly relevant for the upcoming second phase of the energy transformation. The "Energy Technologies and Systems" Division specializes in these topics in its business areas of Energy-Efficient Buildings, Solar Thermal Power Plants and Industrial Processes, Hydrogen Technologies and Electricity Storage Systems, as well as Power Electronics, Grids and Intelligent Systems. In the many projects and results that are presented on the following pages and in the Internet, we pay particular attention to the topic of "Digitalization", which is becoming increasingly relevant for the technological fields associated with the energy transformation. Big Data plays a central role for optimal operation management to achieve energy-efficient buildings. Digitalization helps to increase the efficiency of solar thermal power plants. It not only increases efficiency in the systems integration of storage units in stand-alone PV systems but also for management of the electricity grid. It helps to optimize the operation management strategy for feeding hydrogen into the gas network.

ENERGY-EFFICIENT BUILDINGS

Energy-efficient buildings play a central role in climate protection: More than 40 % of the end energy demand in Germany is caused by the building sector. We must reduce the energy demand for operating buildings and then meet it with renewable energy sources to the greatest extent possible. This is exactly where Fraunhofer ISE makes its contribution: We offer support for consistent realization of this vision, from building planning through construction to operation.

195
Total staff

27
Journal articles and contributions to books

45
Lectures and conference papers

8
Newly granted patents

We conduct research to reduce the demand for space heating and space cooling with optimized building envelopes and to integrate renewable energy sources. New glazing technology, appropriate controls for solar-shading systems and colored glass covers for building-integrated photovoltaics offer diverse options to architects. We develop decentralized ventilation systems and photovoltaic-thermal collectors, e. g. as the source for a heat pump.

Heat pumps are our main focus for supplying heat to buildings. Our work on this technology addresses the entire value chain: from component development for the cooling circuit, through equipment and systems development, to quality assurance in practical operation. Special emphasis is placed on the optimization of heat exchangers and the use of natural refrigerants such as propane.

Thermal storage plays an important role both for the use of fluctuating renewable energy sources in buildings and also for increasing the heating demand flexibility to increase grid-supportive building operation. Storage units for heat and for cooling power are both focal points of our developments. The digitalization of processes is a key technology for sector coupling and to increase energy efficiency. Planning with digital methods such as Building Information Modelling (BIM) helps to preserve the information flow over the lifecycle of a building with a consistent semantic description. Error analyses based on artificial intelligence and its implementation in hardware and software guarantee a high-quality energy supply on the basis of renewable energy sources.

Selected Milestones in 2018

- » Accreditation of the TestLab Heat Pumps and Chillers.
- » Methodology implemented in BIM for digital description of control concepts for operation monitoring of technical building plant.
- » New, more cost-effective production concept developed for building-integrated photovoltaic modules.

1 *Sprinkler system to acoustically couple out the air current for a heat pump.*

www.ise.fraunhofer.de/energy-efficient-buildings

Contacts

Energy-Efficient Buildings
Dr. Peter Schossig | Phone +49 761 4588-5130
Sebastian Herkel | Phone +49 761 4588-5117
building@ise.fraunhofer.de

Building Envelopes
Dr. Tilmann Kuhn | Phone +49 761 4588-5297
building.envelope@ise.fraunhofer.de

Building Operations Management
Nicolas Réhault | Phone +49 761 4588-5352
building.control@ise.fraunhofer.de

Building Systems Technology
Dr. Constanze Bongs | Phone +49 761 4588-5487
Dr. Peter Engelmann | Phone +49 761 4588-5129
building.concepts@ise.fraunhofer.de

Low-Temperature Solar Thermal
Dr. Wolfgang Kramer | Phone +49 761 4588-5096
soltherm.collectors@ise.fraunhofer.de

Heat Pumps
Dr. Marek Miara | Phone +49 761 4588-5529
heatpumps@ise.fraunhofer.de

Thermal Energy Storage for Buildings
Stefan Gschwander | Phone +49 761 4588-5494
building.thermal-storage@ise.fraunhofer.de

Ventilation and Air-Conditioning
Dr. Lena Schnabel | Phone +49 761 4588-5412
building.airconditioning@ise.fraunhofer.de

Selected Projects in 2018

- InDeWaG – Industrial Development of Water Flow Glazing Systems
- RenoZEB – Promotion of Energetic Renovation Solutions for Zero Energy Buildings and Residential Areas
- NEK-Quartiere – Sustainable Use of Renewable Energy for the Delivery of Electricity, Heat, and Cooling in Energy Concepts for Buildings and Districts Under Consideration of Building Energy Efficiency – Initial Research
- SolSys – Analysis and Optimization of Solar Energy Supply Systems
- SCOPE – Project Data Environment and Modelling of Multi-functional Building Products with Focus on the Building Envelope
- SysWärme – Systemic Challenge of Heating Sector Transformation
- WCS-energy – Online Monitoring of Energetic Performance of Wet Cooling Towers

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

New Architecturally Attractive Solar Thermal Concepts

Dr. Bruno Bueno | Phone +49 761 4588-5377 |
building.envelope@ise.fraunhofer.de

Together with architects, façade planners, manufacturers of façade components and craftspeople, Fraunhofer ISE is working on new solar thermal concepts for the building envelope. The common feature of the new solar collectors is a high degree of flexibility. This makes them attractive elements from both design and energy perspectives already in the architectural design phase of sustainable building projects.

We are following different approaches to achieve this. In the "ArKol"[A] project, we have implemented a "dry connection" applying heat pipes to transfer heat from the absorber to the collecting channel. This makes a free choice of position (strip collector) or movement (solar thermal venetian blind) of individual collectors or absorbers possible. In the "TABSOLAR II"[A] project, we applied our membrane vacuum deep-drawing process to produce solar thermal façade elements of ultra-high-performance concrete with integrated channels for the heat-transfer fluid. These elements offer many design options such as surface relief structures, colors and spectrally selective coatings.

In order to gain experience with the new concepts and to measure the solar thermal gains with our test rigs, we successfully transferred our samples from the laboratory to technical prototype scale and constructed demonstration units. In future, further options such as colored coatings or glazing should be addressed so that even more architectural design freedom can be achieved.

1 *Demonstration unit of a façade collector with heat pipes that was prepared within the "ArKol" project.*

Sustainable Heat Supply for Existing Multi-Family Housing

Dr. Constanze Bongs | Phone +49 761 4588-5487 |
building.concepts@ise.fraunhofer.de

By 2050, the goal is to reduce energy-related emission of greenhouse gases by 80 to 95 % relative to the reference year of 1990. The building sector is playing a decisive role toward reaching this climate-protection goal. A combination of using the building envelope to gain energy and reducing CO_2 emissions caused by the heat supply is necessary. A central component to achieve this is low-exergy technology such as heat pipes which use ambient heat. Whereas their application in free standing and semi-detached houses has long since become standard, heat pumps are underrepresented in multi-family housing, particularly in the existing building stock.

In the joint project, "LowEx im Bestand"[A] (Low-exergy for existing buildings), Fraunhofer ISE is developing suitable solutions to meet the needs for efficient space heating technology, hygienic provision of domestic hot water and renovation options which can be applied in occupied dwellings, taking the limited availability of sources in inner-city areas into account. Together with our industrial partners, we are developing heat pumps and ventilation technology to meet these criteria. We are preparing and evaluating holistic system concepts for the application of this technology in multi-family housing with differing renovation standards. In doing so, we take account of the possibilities to use existing hydraulic and heat exchanger systems. Feasibility is proven by the demonstration of selected solutions in real buildings.

2 *Renewable heat supply for renovated multi-family housing from the beginning of the 20th century in Freiburg.*

[A] Supported by the German Federal Ministry for Economic Affairs and Energy (BMWi)

Digital Methods for Energy-Relevant Building Operation Management

Nicolas Réhault | Phone +49 761 4588-5352 |
building.control@ise.fraunhofer.de

The "Internet of Things" (IoT) and the "digital building twin" (Building Information Model, BIM) represent the next evolutionary stages in building automation. These technologies allow additional information about the equipment status to be acquired, distributed and managed digitally. In this way, they provide a better overview of increasingly complex building technology and enables requirements on comfort and energy efficiency to be met better.

In addition, they provide finely resolved measurement data and meta-data for innovative analytical and diagnostic methods. These can be used as input to train and apply machine-learning procedures, which continuously monitor the operation of systems and components. Defects and suboptimal operating states in building operation can thus be recognized quickly and building operators soon receive all the information needed to solve the problem via suitable web platforms such as "Mondas" or "TOPAs".

Parallel to cloud computing, numerical decomposition procedures allow distributed integration of the monitoring methods using inexpensive computer units. Fraunhofer ISE is developing and testing innovative methods for fault detection and diagnosis for technical building plants which are connected to BIM and contribute significantly to increasing the energy efficiency of building operation.

1 *Monitoring the heat-recovery operation of an indoor ventilation system.*

Innovative Operation Management for District Heating

Axel Oliva | Phone +49 761 4588-5698 |
building.concepts@ise.fraunhofer.de

Fraunhofer ISE is comprehensively investigating the future role of the thermal use of solar energy for supplying heat in urban areas. Distributed integration of solar thermal systems into a district heating system that is based on a combined heat and power (CHP) plant is decisive for this topic. We optimize the CHP operation to achieve the best possible interaction with the electricity grid. Operation of the district heating grid is treated with the goal of minimizing distribution losses. The goal is to derive generally applicable rules for long-term thermal use of solar energy in residential districts, particularly against the background of a radically changing energy supply structure.

An example for this conceptional approach can be found in the "Freiburg-Gutleutmatten"[A] demonstration project. A supply concept with the necessary operation management strategies was worked out on the basis of numerical system simulation. At present, the developed operation modes are being transferred into the control strategies for the district and combined with model-based, predictive control (MPC) to achieve optimal operation. An essential feature is the modulating operation mode of the entire district heating network with active integration of the hot water storage tanks that are installed in the individual buildings. During summer, the individual buildings can be provided with sufficient heat from the solar thermal systems for longer periods, so that the district heating system can shut down operation at these times. In addition, heat from solar thermal systems can be fed into the district heating network and be distributed further by it.

2 *Freiburg-Gutleutmatten district.*

[A] Supported by the German Federal Ministry for Economic Affairs and Energy (BMWi)

SOLAR THERMAL POWER PLANTS AND INDUSTRIAL PROCESSES

1

75
Total staff

13
Journal articles and contributions to books

25
Lectures and conference papers

In sunny regions, solar thermal power plants based on concentrated solar power (CSP) already provide dispatchable renewable electricity through the use of large thermal storage units. Particularly in combination with inexpensive PV electricity, the storage potential provided by CSP in grids with increasing proportions of electricity from fluctuating renewable sources will become increasingly important.

Together with our partners, we are conducting research on materials, components, collectors and systems, to further increase the efficiency and reduce manufacturing costs. Cost-efficient and resource-saving operation of the systems is also the subject of current work.

Thermal storage also offers great potential for industrial processes to become more efficient and energy flows to be designed more flexibly. In addition to concrete storage solutions and energy-efficiency measures, we are working on integrating solar process heat into the heat supply for industrial processes. The efficient conversion and transfer of thermal energy can make further contributions to the decarbonization of industrial processes. For this reason, efficient heat exchangers and the materials and components needed for them are a major subject of our research. Questions of humidification and dehumidification form the link to our work on water purification. In addition to preparing drinking water from seawater or brackish water, we are working increasingly on purifying or concentrating residual materials in industrial waste water. 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 can draw on many years of experience from projects on applications in solar thermal power stations and in diverse industrial sectors.

1 *Flexibly configurable test rig to characterize and investigate single-tank storage concepts based on molten salt for temperatures up to 550 °C.*

Selected Milestones in 2018

» Commissioning of the first CSP parabolic trough power plant with molten salt as the heat-transfer fluid and storage medium in the "MATS" project.
» Conference held on saving water in CSP power plants within the "MinWaterCSP" project.
» Successful completion of the "DASTII" project to use solar process heat in industrial processes of the Tunisian food-processing industry.

www.ise.fraunhofer.de/solar-thermal-power-plants-and-industrial-processes

Contacts

Solar Thermal Power Plants and Industrial Processes
Dr. Peter Nitz | Phone +49 761 4588-5410
soltherm@ise.fraunhofer.de

Solar Thermal Power Plants
Dr. Peter Nitz | Phone +49 761 4588-5410
soltherm.systems@ise.fraunhofer.de

Concentrating Collectors
Anna Heimsath | Phone +49 761 4588-5944
soltherm.collectors@ise.fraunhofer.de

Water Treatment and Materials Separation
Dr. Joachim Koschikowski | Phone +49 761 4588-5294
soltherm.water@ise.fraunhofer.de

Thermal Storage for Power Plants and Industry
Dr. Thomas Fluri | Phone +49 761 4588-5994
soltherm.storage@ise.fraunhofer.de

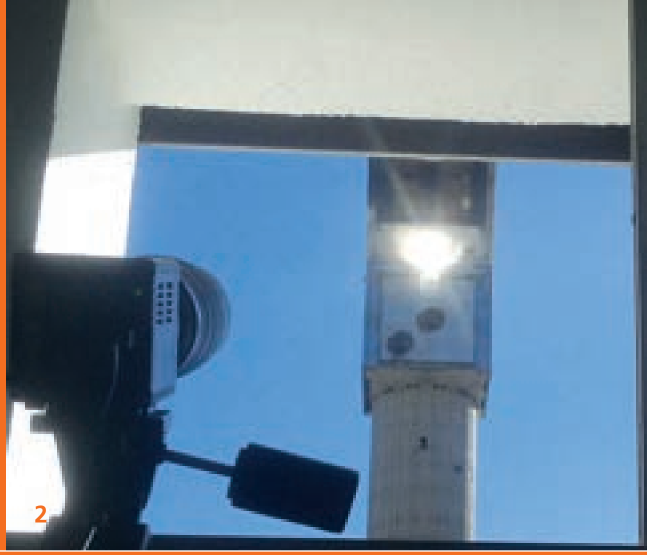
Industrial Processes and Process Heat
Dr. Pedro Horta | Phone +49 761 4588-2126
soltherm.process@ise.fraunhofer.de

Efficient Heat Exchangers
Dr. Lena Schnabel | Phone +49 761 4588-5412
building.airconditioning@ise.fraunhofer.de

Selected Projects in 2018

- Polyphem – Small-Scale Solar Thermal Combined Cycle (Gas Turbine/ORC)
- AVUS – Automated in situ Measurement of Contamination Quotas and Spectrums

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



Digitalization Transforms Operation of Solar Power Towers

Anna Heimsath | Phone +49 761 4588-5944 | soltherm.collectors@ise.fraunhofer.de

Tower-based systems represent a promising technological approach for solar thermal power plants. Up to 50 % of the investment costs for such systems are caused by the heliostat array, which concentrates the incident solar radiation onto a receiver in the tower. High optical quality of the heliostats and their accurate tracking are decisive for the power plant efficiency and the resulting levelized cost of electricity.

The increasing digitalization of solar thermal power plants enables the potential for efficiency to be better exploited and technical challenges to be overcome successfully. Our research approaches lead to the production and control of the heliostat array being linked to the most modern information and communications technology.

For example, we have developed the "HelioControl" imaging control system to accurately check the actual target positions of heliostats during operation. In addition to their solar tracking, individual heliostats are subjected to periodic motion with a very small amplitude, which is recorded in the accumulated focal spot on the radiation receiver by cameras and then digitally analyzed. The real target point of the heliostats is thus determined and – if this deviates from the intended target position as recorded in the control algorithms – used to correct the corresponding heliostat's orientation.

The methodology was tested and demonstrated both on a laboratory scale and in initial field tests with a real heliostat array. Compared to the sequential "calibration" of the heliostat target positions on a separate optical target area, which is customary today, the time and expense needed for controlling the target positions of thousands of heliostats in a large array are reduced significantly. In simulation, we could determine appreciable savings, because the improved target control means that fewer heliostats must be installed to achieve the same power. We hope that further savings can be achieved in the heliostat construction itself, as the quasi-continuous target control means that very accurate operation is still possible even if the tolerances on construction are relaxed slightly.

In the next step, we will cooperate with industry to develop a plug-in system that should make the integration into new and existing heliostat array controls feasible. A further application opportunity for "HelioControl" is the initial calibration of a new solar array during its commissioning. Usage of "HelioControl" could reduce the time needed by a factor of a hundred.

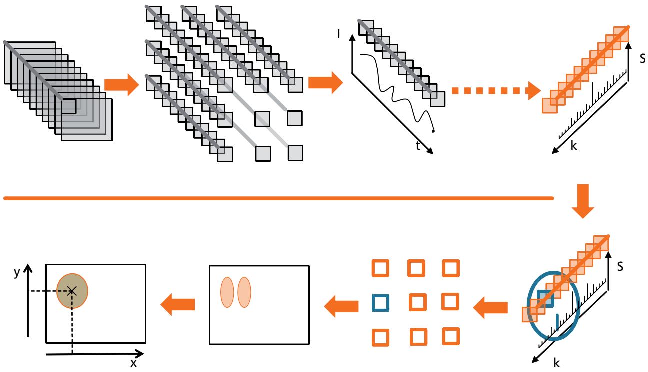


Diagram: Schematic diagram of the "HelioControl" system to check and correct target positions, which is applied as a closed loop in the form of a plug-in for existing commercial solar array controls.

1 *Focal spot test in the heliostat test rig at Fraunhofer ISE.*

2 *"HelioControl" plug-in system being tested on the THEMIS demonstration system belonging to CNRS-PROMES in France.*

Efficient Heat Exchangers for Industrial Processes

Dr. Lena Schnabel | Phone +49 761 4588-5412 | building.airconditioning@ise.fraunhofer.de

For the energy transformation to be successful, it is essential that greater use be made of efficient heat exchangers in industrial processes. Throughout Germany, about 1700 petajoule of process heating and cooling energy is needed in the industrial sector every year. Thus, already slightly increasing the efficiency of heat exchange can have a large effect.

Fraunhofer ISE addresses the whole range of topics concerning heat exchange, from fundamental thermodynamic processes of heat exchange to experimental investigations in the laboratory and the field. At the fundamental level, we optimize heat exchangers to achieve higher energy efficiency, reduced equipment volume and lower mass. Innovative approaches to use metal wire structures to increase the surface area of air-fluid heat exchangers have experimentally demonstrated up to 50 % more compact configurations while retaining the same transfer power. The wires are deliberately positioned parallel to each other and form an oriented porous structure. The air flows through this structure and releases or extracts heat via the wires. At the same time, large amounts of material could be saved with this approach by increasing the surface area, which has a positive effect on reducing the mass of the heat exchanger. In the "MinWaterCSP"[A] project, we have developed heat exchanger designs for air condensers on the basis of fluid-dynamic and thermodynamic calculations, which feature pipes with 10 % less mass for the same increase in surface area. Samples were constructed and measured.

Heat transfer processes and increases in surface area are also very important for thermal energy storage units to provide heating or cooling power efficiently at a later time or a different place. The performance of latent-heat storage units, for example, is limited by the low thermal conductivity of the phase change materials used. Heat exchangers based on micro-tubes with metal wire mesh compensate the low thermal conductivity and enable better coupling of the storage material in the direction of the wire mesh. We apply transient thermodynamic simulation to investigate and optimize the effectivity of this type of heat exchanger for latent heat storage.

We have achieved further optimization for a single-tank thermal storage unit with a molten salt as the storage medium. These storage solutions are applied in the industry and in power plants. With our test rig at Fraunhofer ISE, we demonstrated that the mixing of hot and cold fluids can be minimized by redesigning the inlet. Stratification with a temperature gradient of more than 120 K over 8 cm was achieved. Using our "ColSim" simulation software, we also identified significantly improved operation strategies and better storage management, which achieved a storage utilization factor of around 93 %.

1 *Flexibly configurable test rig at Fraunhofer ISE to characterize and investigate single-tank storage concepts based on molten salt for temperatures up to 550 °C.*

2 *Increased surface area of a flat-pipe heat exchanger achieved with metal textile structures based on wire with a diameter of 180 µm.*

[A] Supported by the European Union (Horizon 2020)

HYDROGEN TECHNOLOGIES AND ELECTRICAL ENERGY STORAGE

1

131
Total staff

16
Journal articles and contributions to books

26
Lectures and conference papers

4
Newly granted patents

With our activities in this area, we offer R&D services addressing the generation, conversion and further thermochemical processing of hydrogen. Within electrochemical generation of hydrogen, we are concentrating on electrolysis of water in polymer-electrolyte membrane electrolyzers (PEM). We also apply PEM technology to develop fuel cell systems, particularly for the mobility sector. For both water electrolysis and fuel cells, we carry out multi-scale physical simulation and fundamental electrochemical characterization of cells and stacks. Our research encompasses the development, simulation and testing of single cells, cell stacks and complete systems as well as the testing of peripheral and cell components under all climatic conditions that can apply. Furthermore, we synthesize liquid fuels and chemicals from hydrogen and carbon dioxide (Power-to-Liquids), applying catalysts that we have developed ourselves. These processes create the link from sustainable electricity generation via water electrolysis to other sectors, such as mobility and chemistry.

For battery materials, cells, modules and systems, we offer R&D services based on conventional and future technology. These encompass the analysis and exploration of new material combinations and cell architecture, the investigation of new manufacturing processes, the construction of battery cells, and their configuration and characterization. We analyze aging mechanisms and approaches to increase cycling stability and lifetime. We also develop entire battery system prototypes, including thermal management and battery management. Beyond this, we accompany our partners within field projects with integration into extremely diverse applications and the corresponding quality assurance. Examples include stationary battery storage units that are used commercially or industrially, as well as applications for electromobility, ranging from light electric vehicles through cars to the electrification or hybridization of ships.

Selected Milestones in 2018

- New study presented: Electrolysis of water has the potential to become a gigawatt industry.
- Commissioning of a hydrogen injection system in Freiburg, Germany.
- High-power battery system with 140 kW and an energy capacity of 5.5 kWh developed and constructed.
- Batteries developed with aqueous electrolytes as a cost-effective, environmentally friendly and long-lived alternative for stationary applications.
- Simulation-based design and optimization of a PV-battery system for direct feeding into a tram network as an example of future-oriented sector coupling.

1 *Battery cell development – assembling a button cell.*

www.ise.fraunhofer.de/hydrogen-technologies-and-electrical-energy-storage

Contacts

Hydrogen Technologies
Dr. Christopher Hebling | Phone +49 761 4588-5195
h2fc.hydrogen@ise.fraunhofer.de

Thermochemical Processes
Dr. Achim Schaadt | Phone +49 761 4588-5428
h2fc.thermoprocess@ise.fraunhofer.de

Electrolysis and Power-to-Gas
Dr. Tom Smolinka | Phone +49 761 4588-5212
h2fc.electrolysis@ise.fraunhofer.de

Fuel Cell Systems
Ulf Groos | Phone +49 761 4588-5202
h2fc.systems@ise.fraunhofer.de

Electrical Energy Storage
Dr. Matthias Vetter | Phone +49 761 4588-5600
batteries@ise.fraunhofer.de

Battery Cell Technology
Dr. Daniel Biro | Phone +49 761 4588-5246
batteries.cell@ise.fraunhofer.de

Battery System Technology
Stephan Lux | Phone +49 761 4588-5419
batteries.system@ise.fraunhofer.de

Applied Storage Systems
Johannes Wüllner | Phone +49 761 4588-2129
batteries.application@ise.fraunhofer.de

Selected Projects in 2018

- Resource Efficiency – Development of Gas Diffusion Layers for Polymer-Electrolyte Membrane Fuel Cells based on Environmentally Friendly and Energy-Saving Raw Materials

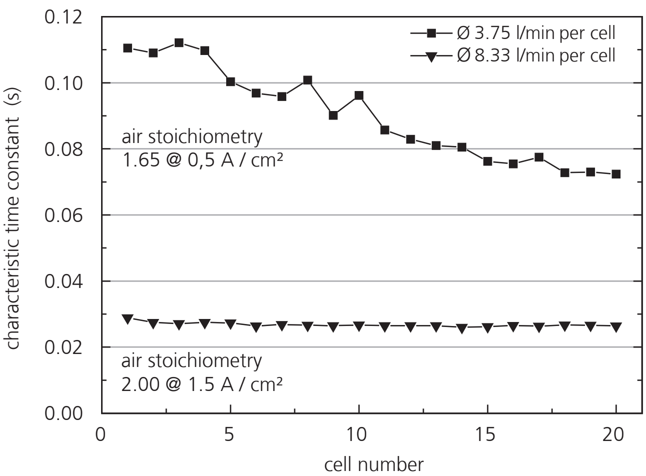
More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/4-00

Characterization of Fuel Cell Stacks

Stefan Keller | Phone +49 761 4588-5207 | h2fc.systems@ise.fraunhofer.de

Fuel cells make emission-free mobility feasible with long cruising ranges and short tank filling times. The central component is the fuel cell stack, which can consist, for automotive applications, of more than 400 single cells. We offer scientifically based characterization with regard to performance as well as long-term stability for short stacks with power of up to 20 kW_{el}.

The performance of a fuel cell stack is determined essentially by its sensitivity to operating parameters like gas supply, gas humidity, operating temperature, gas pressures at the anode and cathode and the stack compression. Fraunhofer ISE therefore carries out corresponding sensitivity analyses. Its 28-channel impedance testing system is unique and allows the impedance spectra of 28 single cells or cell packs to be recorded simultaneously, allowing inhomogeneities within the stack to be detected and analyzed. This is particularly important when so-called "rainbow stacks" with different membrane-electrode assemblies are to be characterized. By applying appropriate voltage contacts, differences in the gas inlets from one single cell to another can also be measured in the stack. The impedance data allow more accurate analysis of the simultaneously occurring physical and electrochemical processes than a simple voltage measurement. Power losses can be understood better and solutions proposed to avoid them. Last year we succeeded in identifying the characteristic time constants for the single cells of a cell stack by innovative analysis of the single cell impedance spectra. This allows a comparative estimate of the flow rate through all of the single cells in the cell stack. The dependence of possible inhomogeneity in the gas supply within the cell stack can be identified in this way.



Graph: Characteristic time constants for a cell stack of 20 single cells for different values of air stoichiometry: Significant inhomogeneity in the flow rate is visible for low air stoichiometry.

In our walk-in climatic chamber, we can investigate cold start strategies down to -40 °C and the operating behavior up to +80 °C. In the "AutoStack-CORE"[A] project, we successfully carried out experiments on cold starts down to -20 °C. A special cooling circuit was constructed in our climatic chamber for this purpose. With the help of impedance spectroscopy, we developed suitable conditioning processes to prepare the fuel cell stack for a cold start. As a result, the fuel cell stack achieved half the rated power already after 13 s during a cold start at -20 °C. This is significantly shorter than the project goal of 30 s.

1 Fuel cell test stand for short stacks of low-temperature polymer-electrolyte membrane fuel cells up to 20 kW_{el}, climatic chamber and multi-channel system for electrochemical impedance spectroscopy.

[A] Supported by the European Union (Fuel Cells and Hydrogen Joint Technology Initiative).

Methanol from Process Gases from the Steel Industry

Max Hadrich | Phone +49 761 4588-2207 | h2fc.thermoprocess@ise.fraunhofer.de

Steelworks account for about 6 % of the German CO_2 emissions. The collective term, "flue gases", designates the process gases which are produced in large amounts at various steps of the smelting process and are rich in hydrogen and carbon oxides (CO_2 and CO). They include coke oven gas, blast furnace gas and basic oxygen furnace gas. At present, flue gases are mainly used thermally to generate electricity and heat. In the "Carbon2Chem©"[A] project, partners from industry and research are investigating various scenarios to use these flue gases as materials and close the carbon cycle. Fraunhofer ISE is studying the synthesis of methanol. Methanol, an important basic chemical and potential fuel, is produced almost exclusively from fossil sources (natural gas, coal) today. Three particular challenges are posed by synthesis using flue gases: Firstly, the flue gases must be purified. Secondly, their high CO_2 content makes them an unusual starting material for methanol. Thirdly, the utilization of flue gases imposes high demands on the equipment dynamics, as the amounts and compositions can fluctuate considerably.

Fraunhofer ISE is investigating the topic by means of simulations and experiments. The dynamic behavior of methanol synthesis is the greatest unknown factor, because it is currently carried out under almost unchanging conditions, like most large-scale technical syntheses. However, as the flue gases reflect the dynamics of the steelwork and energy from fluctuating renewable sources will be introduced, the system components needing particular attention must be identified.

1 *Detailed view of the methanol mini-plant. The reactor is equipped with several temperature sensors. The insulating jacket is used for heating.*

In parallel, experiments are being carried out, initially with synthetic flue gases, in a fully automated mini plant that was designed, constructed and commissioned by Fraunhofer ISE. Insights gained from the simulations can thus be tested directly and the simulations can be experimentally validated. The system is equipped with a two-stage, quasi-adiabatic reactor system, which means that in contrast to isothermal reactors, no cooling circuit is needed. Unreacted educts are separated and reintroduced into the synthesis. A commercially available CuZnAl catalyst in pellet form from Clariant, a project partner, is used.

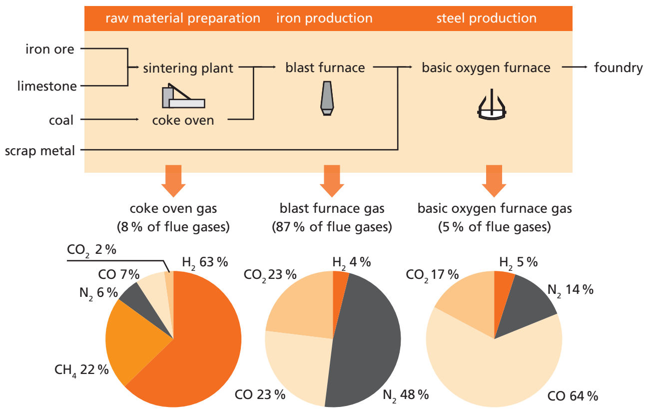


Diagram: Sources, relative amounts and compositions of flue gases from steel production.

After the test phase at Fraunhofer ISE, the facility is to be operated under real conditions at the steelwork of thyssenkrupp AG in Duisburg, Germany. There, catalyst poisons will first be removed from the flue gases in a gas purification step and additional hydrogen will be provided from electrolysis.

[A] Supported by the German Federal Ministry for Education and Research (BMBF)

1

Hydrogen Injection: Part of Electrolysis Business Models

Christopher Voglstätter | Phone +49 761 4588-5357 | h2fc.electrolysis@ise.fraunhofer.de

A great advantage of using hydrogen in the gas network is that the required storage and distribution infrastructure is already available. Hydrogen can be fed into the German natural gas network with its enormous storage capacity, which is already very cost-effective. In addition, "green" hydrogen produced with at least 80 % eco-electricity is treated equivalently to biogas by the German energy economy law EnWG (and thus the ordinance concerning access to the gas network GasNZV). This significantly improves the economic boundary conditions and the operational flexibility for hydrogen injection.

To test Power-to-Gas systems in the municipal context and operate them with maximum economic and system-supportive benefits, Fraunhofer ISE carried out the "Freiburg Municipal Energy Association"[A] project together with other partners. As part of it, Fraunhofer ISE installed a modular hydrogen injection system in the local gas distribution network.

The heart of the system is an electrolyzer with an electric connection power of 120 kW and a small hydrogen storage unit (the content corresponds to around 300 kWh of chemically stored energy), which enables slight temporal decoupling from the electricity grid and gas network. The location, construction and controls of the system are designed to also serve as a research platform, where new natural gas or hydrogen components, operating strategies or innovations to the gas network can be tested and investigated under real conditions. Several operating strategies to manage the system have already been developed, optimized in simulation environments and transferred to the real system. The applied operation management is based on the method of model-predictive control to optimize the usage of storage, feed-in capacity and day-ahead purchase of electricity. The operating goal is to use inexpensive "surplus" electricity in combination with incentives to use locally generated electricity from renewable sources, so that operation is as beneficial as possible to the system and the network, taking economic boundary conditions into account. The control algorithms have operated the system for several months. They demonstrated very robust operation due to a sliding calculation horizon and were able to tolerate deviations from predictions, disturbances and occasional outages of system components.

The gas network with its extremely inexpensive storage is an essential component of the energy system. Via injection into the natural gas network, this storage capacity can already be used indirectly by small and medium-sized hydrogen plants: By using injection into the gas network as part of the gas distribution strategy, more flexibility can be created at low cost. With the installation of this research platform, Fraunhofer ISE can conduct further research in this important field for reliable energy supply based on renewable sources.

1 *Unit at Fraunhofer ISE to feed hydrogen into the natural gas distribution network.*

[A] Supported by the State Ministry for the Environment, Climate and Energy Economy in Baden-Württemberg, via the project agency established at the Karlsruhe Institute for Technology

1

Electrolysis of Water: Potential for a Gigawatt Industry

Dr. Tom Smolinka | Phone +49 761 4588-5212 | h2fc.electrolysis@ise.fraunhofer.de

The electrolysis of water to produce hydrogen on the basis of electricity generated from renewable sources is increasingly evolving to become a core technology for the energy transformation. In the form of hydrogen, the rising share of fluctuating wind power and photovoltaic electricity can be stored seasonally, converted back into electricity or further processed to produce fuels and chemical raw materials.

In a study for the German Federal Ministry of Transport and Digital Infrastructure (BMVI), we cooperated with the Fraunhofer Institute for Production Technology and Automation IPA and the E4tech consulting company to develop a road map for establishing the electrolysis of water in Germany. The study demonstrates how the required industrial production capacity for electrolyzers can be established in the near future and which challenges exist concerning the growth of a gigawatt electrolysis industry in Germany.

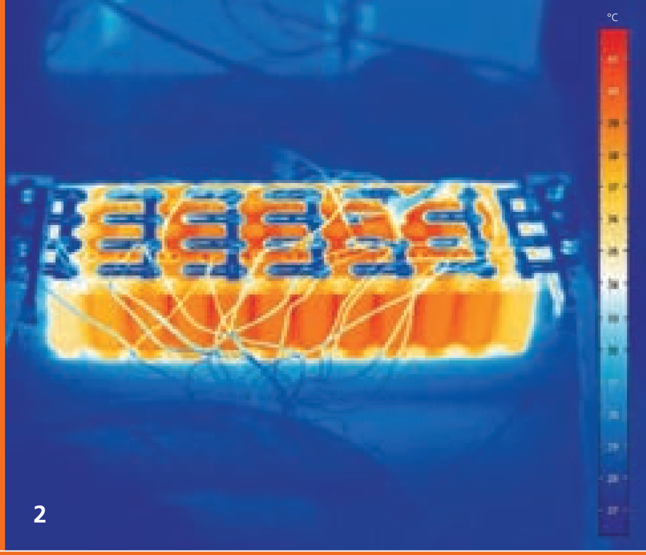
The future demand for electrolyzers for the transport, heat and electricity sectors was determined in an energy system simulation for Germany, applying the "REMod-D" tool developed at Fraunhofer ISE. Several different growth scenarios were considered to take account of the bandwidth of performance parameters that were determined in a survey of the industry. Assuming that the German climate protection goal of reducing energy-related CO_2 emissions by 80 % will be met without large scale import of synthetic fuels, a growth corridor in the range from high tens to hundreds of gigawatts results for the installed electrolysis capacity by 2050. Already in the second half of the coming decade, the incremental growth rate for new installations must clearly exceed one gigawatt per year. From the 2030's onward, the scenarios assume several gigawatts of new installations each year.

Alkaline and PEM electrolysis are already at an advanced technological level today. Although the investment costs still must be halved in future to below 500 €/kW and the lifetime should be extended by continuous further development, both processes can already be applied today on a large scale. From the perspective of production technology, few obstacles were identified, as the processes for component production are already implemented on large industrial scale in other branches.

Action is needed particularly on the part of the lawmakers: the market ramp-up, which is the central lever for further technological development and cost reduction, must be supported by adaptation of the regulatory framework, particularly concerning the purchase of electricity, in order for electrolyzer applications to become economically viable. A "Market Activation Program for Water Electrolysis" is thus proposed, which offers investment planning certainty for manufacturers and users.

The study (in German) and an English summary can be downloaded free of charge from the website of NOW GmbH: https://www.now-gmbh.de/de/service/publikationen

1 *Production of high-temperature cells, such as are also used for electrolysis of water.*



Environmentally Friendly Zinc-Ion Battery of the Next Generation

Dr. Daniel Biro | Phone +49 761 4588-5246 |
batteries.cell@ise.fraunhofer.de

The increasing amount of energy from renewable sources in the power supply results in electricity surpluses in the power grid at times with good generation conditions and low consumption in the daily cycle. In order to make full use of these valuable energy resources, suitable stationary electric storage units are becoming increasingly important for power supply and its reliability. Battery storage units are particularly well suited for storing surplus electricity over the course of a day.

The goal of our research project is to identify safe and environmentally friendly battery cell technology, to characterize it and investigate its cycling capacity and suitability for manufacturing. Battery cells based on aqueous chemistry are inherently safe and can be produced from inexpensive materials. Zinc as the anode and as a charge carrier offers the advantage that no other active materials than a sheet of zinc must be processed to produce the anode.

On the cathode side, manganese oxides are being investigated and processed together with different additives to form printable pastes; we are examining various production procedures in this work. We are paying particular attention to the development of a suitable electrolyte, as this is crucial for the cycling stability of the battery cell. The inexpensive, widely available raw materials and the avoidance of cost-intensive production steps would enable cells based on this chemistry to be manufactured and applied as inexpensive stationary storage units for electricity on a broad basis.

1 *Battery storage units developed at Fraunhofer ISE with aqueous zinc-ion cell technology.*

Lithium-Ion High-Power Storage Units to Buffer Peak Loads

Stephan Lux | Phone +49 761 4588-5419 |
batteries.system@ise.fraunhofer.de

Many devices that are operated with electricity from the grid require high connection power. The resulting peak loads often need to be met for only short periods of time. The required connection power can be reduced many times if a high-power storage unit based on lithium-ion cells is integrated. This would make it feasible to operate devices which usually must be permanently connected to a three-phase circuit with an ordinary household plug and socket. Depending on the design, off-grid operation would also be possible for a certain time.

To allow integration into existing equipment, the challenge is to construct a compact, high-power storage unit and simultaneously to ensure that produced heat losses can be dissipated safely. The goal is to ensure safe and reliable operation at all times and to minimize aging of the applied lithium-ion cells.

Fraunhofer ISE characterizes suitable lithium-ion cells both electrically and thermally, and uses this as the basis to develop high-power systems with the associated operation management strategy. Recently, a corresponding storage system with an energy capacity of 5.5 kWh was constructed, which can provide a maximum power of 140 kW. The battery storage unit operates with a system voltage of 550 V and communicates via a CAN bus.

2 *Thermographic image of a battery module to evaluate heat generation as a function of the discharge power.*

PV-Battery Stand-Alone Grids: Simulation, Design, Quality Control

Johannes Wüllner | Phone +49 761 4588-2129 |
batteries.application@ise.fraunhofer.de

Isolated mini-grids based on electricity generated from renewable sources and equipped with a grid-forming battery-powered inverter can reduce the levelized cost of electricity significantly, particularly in remote areas. The establishment of large isolated mini-grids, e. g. for industrial parks or even whole towns, is particularly complex, as the grid-topological distribution of generators and battery storage units must be optimized, taking land prices and infrastructure costs into account.

Independent studies on system design and quality assurance during the planning phase can clearly reduce the risk for project developers, investors and insurance companies. This forms the basis for bankability and insurability to guarantee performance for this type of capital-intensive electrical infrastructure.

In the "Square Kilometre Array (SKA)"project, a radio telescope with more than 130 000 antennas will be installed over an area of more than 1500 km^2 in Western Australia. The geographical distribution of the load and supply of the total energy demand of about 25 GWh per year is intended to be provided by several large isolated mini-grids. Fraunhofer ISE prepared an optimized system design for this project, including the necessary simulation of the PV-battery power supply and an economic feasibility study. Furthermore, we achieved holistic quality assurance for the project from the planning side with recommendations on component selection and optimization of the system integration.

1 *Electricity supply for the Murchison Radioastronomy Observatory (MRO) in Western Australia with a large isolated mini-grid.*

Innovative Photovoltaic DC Charging Infrastructure with Buffer Storage

Johannes Wüllner | Phone +49 761 4588-2129 |
batteries.application@ise.fraunhofer.de

As the appreciable growth in charging infrastructure for electric vehicles can lead to local supply shortages in the distribution grids, particularly fast charging stations are increasingly being equipped with local storage buffers. In a solar carport with integrated buffer storage and fast charging infrastructure, the DC electricity generated by the PV system can be inverted and rectified up to four times on its route from the PV module via the buffer storage unit to the DC charging point. This creates unnecessary losses.

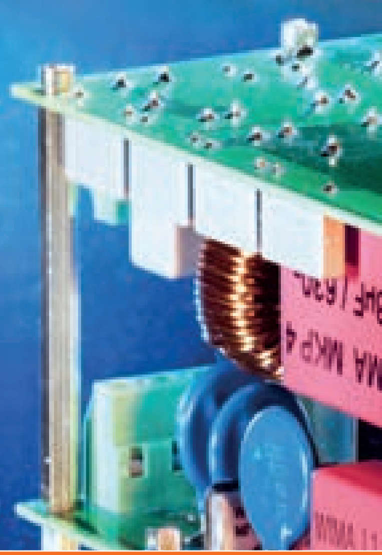
Within the "EnStadt:Pfaff"[A] joint research project, Fraunhofer ISE is investigating and demonstrating purely DC-DC connected fast charging infrastructure. The goal is to increase the efficiency of this type of sector coupling significantly. To this purpose, a DC grid consisting of innovative DC fast charging points, PV generators, a battery system with a high discharge power and a bidirectional inverter as a back-up for grid connection were set up in the urban laboratory center in Kaiserslautern (see page 67). This infrastructure will be evaluated and optimized as part of the demonstration.

Fraunhofer ISE supports industrial partners in identifying innovative solutions by designing, dimensioning and optimizing this type of conductive or also inductive fast charging systems with buffer battery storage for novel applications. These also include charging infrastructure for maritime applications and the electrification of local public transport systems.

2 *Direct and efficient sector coupling of photovoltaics and electromobility is important for both, the energy and the transport transformation.*

[A] Supported by the German Federal Ministries for Economic Affairs and Energy (BMWi) and Education and Research (BMBF)

POWER ELECTRONICS, GRIDS AND SMART SYSTEMS



In its work on Power Electronics, Grids and Smart Systems, Fraunhofer ISE mainly addresses research topics from the electricity sector. We are working on optimizing the interaction between efficient generation from renewable sources, a reliable supply for consumers, energy storage and stable operation of electricity grids. Furthermore, coupling between energy sectors, e. g. the transport or building sectors, represents another important aspect of our activities. Power electronics is becoming an increasingly important technology for the future energy supply.

148 Total staff

14 Journal articles and contributions to books

25 Lectures and conference papers

1 Newly granted patent

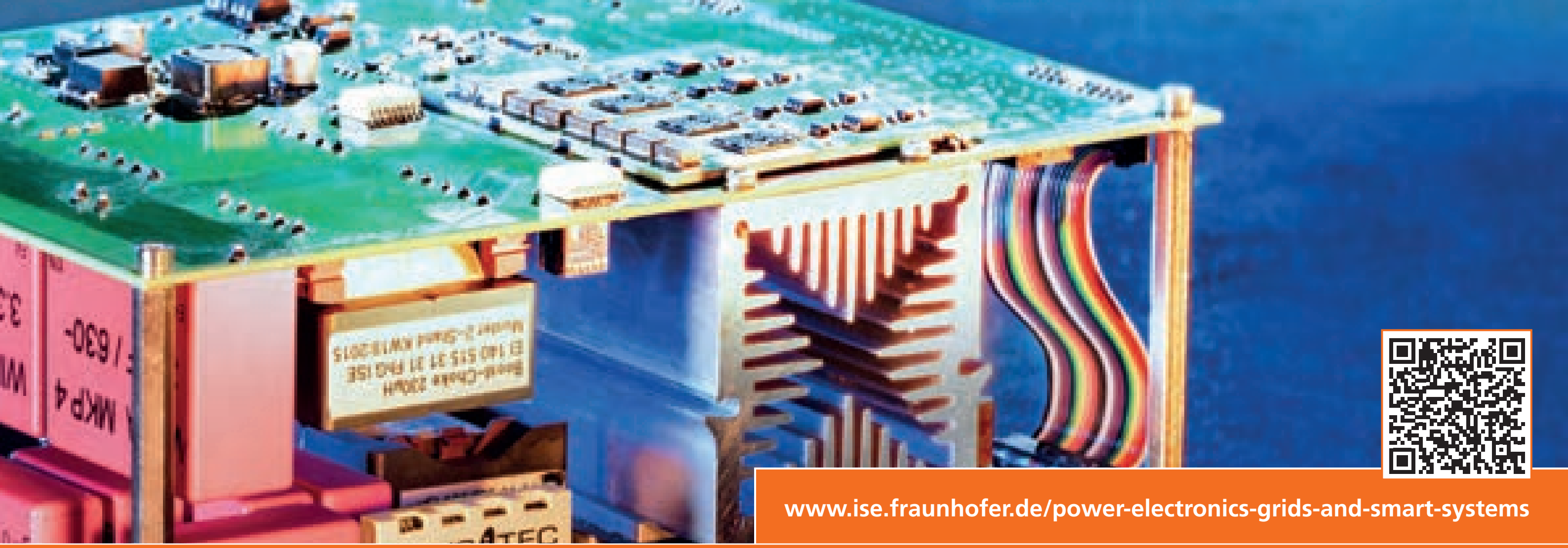
By applying disruptive technologies such as silicon carbide or gallium nitride semiconductors, we are developing significantly more compact, more efficient and less expensive inverters. Not only renewable sources of energy but also electromobility profits from these developments with high-performance and grid-supportive charging infrastructure and longer cruising ranges with efficient on-board converters. The growing dissemination of photovoltaics, heat pumps and electric vehicles stretches the load capacity of the electricity grid to its limits in many places. Shortages and dynamic instability occur more frequently as a result. We are thus working on better grid integration of distributed energy systems. "Grid-supportive operation" of e. g. PV or battery systems, depends both on compliance with the relevant guidelines and on optimal integration of the systems into the energy market.

Digitalization plays an important role in this process. In addition to simulation and optimization of electricity grids to achieve a greater capacity, we are also researching novel information and communications technology, including artificial intelligence methods. Our goal is to enable power plants to organize themselves autonomously, so that they can jointly respond better to challenges from applications or the system. Beyond this, we develop digital models for holistic analysis of energy systems. These provide techno-economically optimal conversion routes for the inter-sectoral energy transformation, and are very important both for smart cities and also in regional and transnational contexts.

Selected Milestones in 2018

- Development of an extremely fast charging system for electric cars.
- Commissioning of the new facilities in the Multi-Megawatt Lab.
- Commencement of planning for the future Digital Grid Lab.
- Operation of new high-voltage silicon carbide inverter to stabilize medium-voltage distribution grids.
- Development of a dynamic electricity tariff system based on ripple control.

1 *2 kW PV inverter.*



www.ise.fraunhofer.de/power-electronics-grids-and-smart-systems

Contacts

Power Electronics, Grids and Smart Systems
Dr. Olivier Stalter | Phone +49 761 4588-5467
energysystem@ise.fraunhofer.de

New Devices and Technologies
Prof. Bruno Burger | Phone +49 761 4588-5237
energysystem.components@ise.fraunhofer.de

Power Converter Systems
Stephan Liese | Phone +49 761 4588-5890
energysystem.converters@ise.fraunhofer.de

Inverters in Power Grids
Sönke Rogalla | Phone +49 761 4588-5454
energysystem.power@ise.fraunhofer.de

Smart Grids
Prof. Christof Wittwer | Phone +49 761 4588-5115
energysystem.grids@ise.fraunhofer.de

Energy Systems Analysis
Dr. Thomas Schlegl | Phone +49 761 4588-5473
energysystem.analysis@ise.fraunhofer.de

Selected Projects in 2018

- Sozio-E2S – Influence of Socio-Cultural Factors on Transformation Paths of Germany's Energy System
- NEK-Quartiere – Sustainable Use of Renewable Energy for the Delivery of Electricity, Heat, and Cooling in Energy Concepts for Buildings and Districts Under Consideration of Building Energy Efficiency
- EDGE – Increasing the Overall Efficiency of Self-Consumption Systems
- DiGO – Distribution Grid Optimization
- DyConPV – Highly Dynamic Control of Photovoltaic Inverters
- SysWärme – Systemic Challenge of Heating Sector Transformation
- HiPoInd – High Power Inductive – Automated, Wireless Fast-Charging Technology for Autonomous Mobile Robots and Industrial Trucks

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/5-00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New Laboratory Center Starts Operation

Sönke Rogalla | Phone +49 761 4588-5454 |
energysystem.power@ise.fraunhofer.de

As part of the "Center for Power Electronics and Sustainable Grids" (see page 83) at the new Zinkmattenstrasse location in Freiburg, Fraunhofer ISE has taken three new laboratories into operation. With the Power Converters Lab, the Multi-Megawatt Lab and the Medium-Voltage Lab, unique facilities are now available for research and development on power electronics and dynamic grid control. These reinforce the leading position of our Institute in the international research landscape and enable it to meet impending challenges in the electricity sector.

Direct Connection to the High-Voltage Grid

The new laboratory premises has its own connection to the 110 kV high-voltage grid. Our own 40 MVA voltage transformer feeds a proprietary research grid which allows the investigation – without disturbing third parties – of the effects of voltage changes, the propagation of harmonics between the low-voltage, medium-voltage and high-voltage grids, and special grid situations such as islanded grids. The medium-voltage transformers with different power ratings up to 6.4 MVA and variable voltages between 260 V and 36 kV are available to supply power to the test fields in the laboratory.

1 *Outdoor view of the new premises in the Zinkmattenstrasse, Freiburg.*

2 *Indoor view of the new Multi-Megawatt Lab.*

3 *Medium-voltage switchboard for connecting the test field transformers and testing facilities.*

Power Electronics in the Multi-Megawatt Range for Low and Medium Voltages

In the low-voltage range, Fraunhofer ISE has created the technical conditions to operate power converters up to the multi-megawatt range. With this, we are equipped for current and future developments of e. g. larger PV and battery inverters. Furthermore, laboratories equipped with special safety technology allow the development of power electronics with a direct connection to the medium voltage grid. Power electronic devices can be operated in a large climatic chamber at temperatures between -30 °C and +80 °C and adjustable humidity, to allow reliability and lifetime questions to be investigated. The activities focus on efficient, compact and reliable inverter approaches for grid applications, railway or medical technology, and also novel system concepts e. g. for PV and wind power plants, battery systems, electrolyzers or larger electricity supply systems.

Inverters for Reliable Grid Operation

Modern inverters can stabilize the electricity grid and must be further developed to make them future guarantors of reliable grid operation. Their electrical characteristics are decisive for this role. Our highly dynamic 1 MVA grid simulator allows us not only to investigate the reaction of inverters to dynamic changes in grid frequency and grid voltage, but also to analyze their harmonic behavior, e. g. by impedance spectroscopy. Furthermore, test rigs for RLC resonators are applied to investigate the behavior of islanded grids. Our new, high-performance Fault Ride-Through facility enables the dynamic behavior of generator systems to be tested not only for under-voltage ride-through (UVRT) during short periods of

low voltage but also for over-voltage ride-through (OVRT). An important research focus is the development of voltage-controlled and grid-maintaining inverters for future electricity grids with a large share of renewable sources, as well as tests of micro-grid applications and improvements in control technology.

Aggregation of Competence and Services for Power Electronics

Our activities in the medium and low power ranges are now also located in the new premises. They encompass research, development and testing of new components and technology, of converter systems close to production readiness and power electronics in grids. We deploy this concentrated competence in diverse applications, e. g. in photovoltaics, energy storage, charging infrastructure for electromobility, electricity grids, railways, aviation and space transport. Our accredited TestLab Power Electronics (see page 75) also profits from the new premises with an expansion of the addressed power range and the extent of the offered characterization and testing services. The electrical properties of the test objects can be analyzed with greatest precision due to the existing, highly accurate power measurement technology.

The project was supported by the German Federal Ministries for Economic Affairs and Energy (BMWi), for Education and Research (BMBF) and for the Environment, Nature Conservation and Nuclear Safety (BMU), which provided a total of 10 million euros to Fraunhofer ISE. Fraunhofer ISE itself invested a further 5 million euros in the new laboratory.

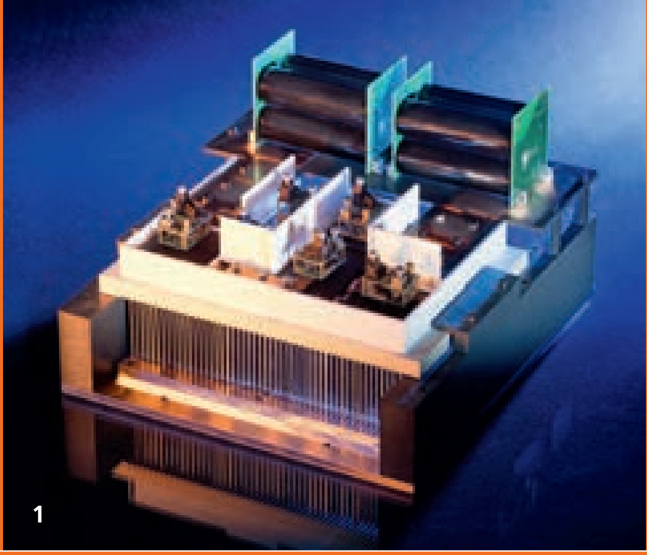
Requirements on Intelligent Grids

Prof. Christof Wittwer | Phone +49 761 4588-5115 | energysystem.grids@ise.fraunhofer.de

Restructuring the public power supply to accommodate a large proportion of electricity from renewable sources poses major challenges to the electricity grid, its components and their operation management. Both the electric and communication requirements on these grid constituents are changing. In addition, the need to equip them with local but simultaneously interconnected intelligence is growing. However, these components cannot be tested and further developed during grid operation, except in special cases.

Fraunhofer ISE will therefore extend its competence in the fields of grid simulation and real-time communication environments. Our goal is to model complex grid arrays and operating situations flexibly on a laboratory scale, thus enabling detailed investigation of the behavior of devices or equipment at grid nodes. The test environments should make both stationary and also dynamic experiments feasible in a power range up to several hundred kilowatts.

In this way, Fraunhofer ISE will extend its important research focus on digitalization to the operation management of components. It also allows the analysis of interactions between components and the electricity grid to be further expanded. In particular, we will intensify our investigations of the grid connection of infrastructure for electromobility, aspects concerning the systems technology and operation management of micro-grids, and the automation of grid and system operation.



Stabilization of Medium-Voltage Distribution Grids

Prof. Bruno Burger | Phone +49 761 4588-5237 |
energysystem.components@ise.fraunhofer.de

By applying new silicon carbide (SiC) transistors with a blocking voltage of 15 kV, Fraunhofer ISE has developed a new inverter which can feed directly into the medium-voltage grid without a transformer. Due to the high blocking voltage of the transistors, a simple three-level circuit could be chosen, unlike conventional approaches. By contrast, commercially available equipment must use complex multi-level circuits with a large number of components to achieve the required operating voltages. The applied SiC transistors also feature very low switching losses, allowing high switching frequencies. This means that the passive components can have smaller dimensions, saving material and mass for capacitors and inductors. A further advantage of this technology is the wider dynamic range for the inverter controls. The high switching frequency allows the inverter to be applied as an active filter, e. g. to compensate upper harmonics in the medium-voltage grid. This is possible with conventional inverters only to a limited extent, as these use a 50 Hz transformer which acts as a low-pass filter. However, the application of SiC transistors with their high reverse voltage is also accompanied by new challenges. The extremely high voltage gradients during the switching of the transistors can create disturbances or lead to partial and surface discharge in insulating components. The demonstration device feeds 100 kVA into the three-phase 10 kV grid and this power rating is expected to increase in future. The switching frequency of 16 Hz is a factor of about 10 higher than medium-voltage converters with conventional transistors.

1 *Single-phase power stack with 15 kV SiC MOSFETs, drivers and associated intermediate circuit condensers.*

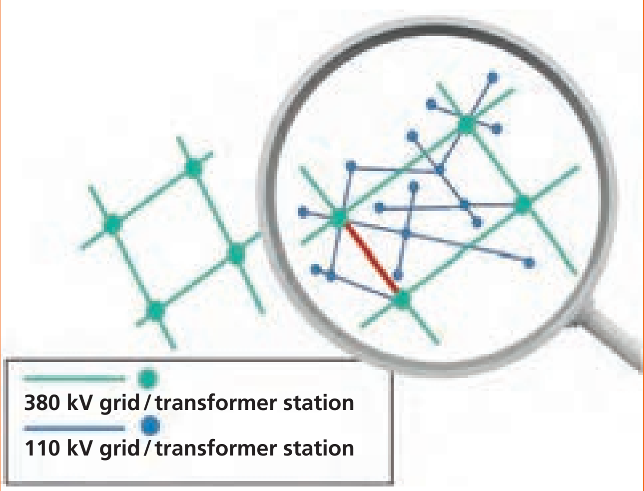
Hybrid Inverter for Grid and Stand-Alone Operation

Dr. Christoph Siedle | Phone +49 761 4588-5420 |
energysystem.converters@ise.fraunhofer.de

Whereas converters previously simply fed electricity into the grid, in future they will have to form the grid and be able to operate it stably. To do this, it is necessary to turn away from conventional current controllers and follow a new approach. As conventional grids are formed by synchronous generators, an obvious option is to impose a similar behavior on converters. So-called "virtual synchronous machines" are detailed mathematical models of the physical structure of the real equivalent. However, this demands powerful processors in the inverters and makes their configuration complicated. Furthermore, they usually cannot be implemented in single-phase systems.

By contrast, the new approach operates the inverter in a voltage-regulated mode with an additional artificial ohmic-inductive impedance. A grid-compatible fixed structure is superimposed for synchronisation with the grid or parallel operation with other generators. This structure needs only a few parameters and does not require high computing power. The artificial impedance has a dampening effect and enables stable operation and well defined load distribution of converters that are connected in parallel. Single-phase or three-phase implementation is possible. The concept is also suitable for application in uninterruptible power supplies (UPS), which ensure that the connected loads are supplied continuously with power without any grid fault interference. After mains return, a reconnection is possible without any interruption.

2 *Development of model-based control-algorithms for converters at Fraunhofer ISE.*



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Holistic Grid Congestion Management in the Electricity Grid

Prof. Christof Wittwer | Phone +49 761 4588-5115 | energysystem.grids@ise.fraunhofer.de

Due to the growing number of PV and wind power plants, stable grid operation in Germany is currently achieved by so-called “congestion management”. Its goal is to minimize the throttling of electricity fed in from renewable sources and to make use of flexibility in the electricity grid. The costs for the national congestion management currently exceed 1.4 thousand million euros and are paid by the final customers via their grid service charges. The transmission grid operators are responsible for grid stability and the integration of the distribution grids into the congestion management via the so-called “coordination cascade”. Therefore, determining the flexibility potential of the subordinate grids plays a central role, but the conventional feedback from distribution grid operators no longer meets the increasingly complex requirements.

As part of the SINTEG showcase project, “C/sells”[A], Fraunhofer ISE has developed a complex simulation model of the German high-voltage grid with more than 8500 nodes. It resolves the spatial distribution of loads and generation at the node level. The data and models are based on the “osmTGmod” open sources and the “OpenEnergy” platform. In addition, we have carried out simulation studies on grid operation with “congestion scenarios” with and without taking account of the subordinate 110 kV grid. This demonstrated that the influence of the high-voltage grid is relevant and thus that significantly smaller corrections to power plant operation could be enough in future.

1 *Highest-voltage grid with subordinate high-voltage topology.*

Development of Smart City Technology in Living Labs

Gerhard Stryi-Hipp | Phone +49 761 4588-5686 | energysystem.analysis@ise.fraunhofer.de

Future urban neighborhoods will require a highly efficient energy system, use local sources of renewable energy as extensively as possible and draw on regional wind power and biomass potentials. This demands sector coupling of the electricity, heat, cooling and mobility sectors as well as the exploitation of flexibility and intelligent energy management systems. Furthermore, the different energy infrastructures will be connected digitally, such that optimal operation of the diverse energy sectors and new business models for energy suppliers and prosumers become feasible.

The increasing complexity of municipal supply structures requires development, evaluation and optimization to be done in so-called “Living Labs”. Urban neighborhoods are preferred experimental spaces for this purpose, as they feature complex infrastructures and a wide range of actors, so that synergetic effects resulting from optimized interaction and intelligent control can be investigated and exploited.

Fraunhofer ISE conceives and coordinates Living Labs projects and is responsible for the scientific management of the “EnStadt:Pfaff”[A,B] lighthouse project in Kaiserslautern, Germany, among others. Nine partners are cooperating to develop the former production site of the Pfaff sewing machine manufacturer to become a sustainable neighborhood for technology, health and residence. Technological development on energy supply, buildings, electromobility and digitalization will be accompanied by sociological investigations.

2 *In the Living Lab Center of the “EnStadt:Pfaff” project, users will be involved in optimizing solutions.*

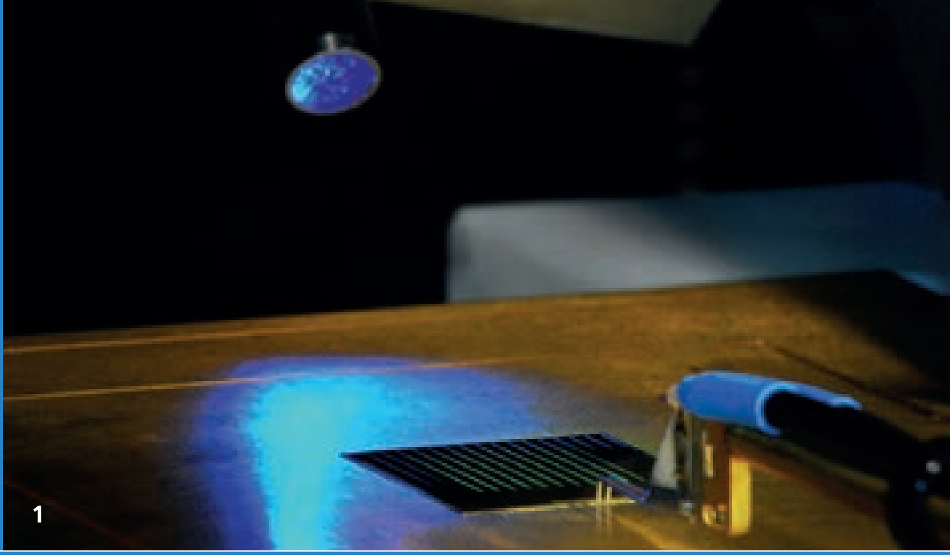
[A] Supported by the German Federal Ministry for Economic Affairs and Energy (BMWi)
[B] Supported by the German Federal Ministry for Education and Research (BMBF)

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 with highly modern technical equipment, which are accredited by the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body):

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

i *Inverter test in the TestLab Power Electronics.*



Calibration of Solar Cells

cells@callab.de

CallLab PV Cells at Fraunhofer ISE offers the calibration and measurement of solar cells representing a wide range of PV technology and works with companies and institutes at national and international levels to develop accurate measurement methods for new types of technologies. 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 tolerances and developing new measurement procedures. Our recent development work has addressed bifacial solar cells and the contacting of novel metallization structures. We have developed new contacting methods for back-contact cells, shingle cells and bifacial cells, which make reliable and inexpensive, individual contacting solutions feasible for these technologies.

Furthermore, a measurement methodology was developed to evaluate meta-stable solar cells, like perovskite solar cells (PSC), comparably to other solar cell technologies. We can now also measure PSC/Si multi-junction solar cells reliably, drawing on our many years of experience with multi-junction solar cells. Various multiple-source simulators allow us to make measurements under almost any standard conditions, such as are needed for space and concentrator applications. In a new research field, we are addressing the measurement of photovoltaic cells for laser power conversion and particularly cells which consist of identical monolithic cell stacks with up to 12 pn junctions.

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.

CalLab
PV Cells

Silicon, Thin-Film, Perovskite, Organic Solar Cells
Dr. Jochen Hohl-Ebinger
Phone +49 761 4588-5359
Wendy Schneider
Phone +49 761 4588-5146

Multi-Junction and Concentrator Cells
Dr. Gerald Siefer
Phone +49 761 4588-5433

Standards and Specifications

- Accreditation as a calibration laboratory according to DIN EN ISO / IEC 17025
- AM1.5g (IEC 60904-3)
- AM0 (ISO 15387)
- AM1.5d (ASTM G173-03)

1 *Spectral response measurement of a multi-junction solar cell in the grating monochromator test bench. In addition to the green test illumination, blue bias light can be seen, which is used to bring the sub-cell to be measured into a current-limited state.*

Performance Tests and Yield Monitoring of PV Modules

modules@callab.de

CalLab
PV Modules

The output power properties of PV modules are decisive for the return on investment of PV power plants. The exact power rating and the low-light performance of the modules are important input information for simulating yields at the site of a PV power plant.

In the accredited calibration laboratory, we apply our extremely accurate performance tests to determine the module power for relevant operating conditions. This can significantly reduce uncertainty in yield simulation. Photovoltaic modules can be calibrated under standard test conditions with a measurement uncertainty of only 1.3 %. By optimizing the solar simulator for power rating measurements (IEC 61853), we have improved the accuracy particularly under low light conditions. This means more certainty for investors in PV power plants.

We compare our laboratory measurements to highly resolved DC measurement data (IV characteristic curves) from our module monitoring in the field. This information is used to increase the accuracy of yield simulation. Additional yields, e. g. from bifacial PV modules, can be determined very accurately in this way. Due to the continuously acquired data, we can also determine degradation effects over longer periods of time.

As part of our quality benchmarking, we apply individual testing procedures to support both the selection of module suppliers for large PV projects and the quality assurance during procurement of large charges of modules. In liability cases, our independent measurements can help to determine deviations from guaranteed power more accurately.

We 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.

Frank Neuberger
Phone +49 761 4588-5280
Mobile +49 170 9247193

Standards and Specifications

» Accredited 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
» Accurate measurement according to IEC 60904-3 with a measurement uncertainty of only 1.5 %
» Power Rating measurements according to IEC 61853
» Module monitoring with highly resolved DC measurement data (IV characteristic curves)
» Evaluation of CPV modules according to IEC 62670-3 under CSOC and CSTC

1 *Accurate yield measurement of different PV modules.*

Quality Assurance of PV Modules

tlpv@ise.fraunhofer.de

TestLab
PV Modules

TestLab PV Modules has offered a broad spectrum of services focusing on quality and reliability testing since 2006. Our accredited laboratory is equipped with extremely modern 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 programs 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. For new technologies, e.g. bifacial modules, we develop standard test procedures further to obtain informative results, taking their special technical features into account. We apply innovative and recently developed analytical methods to systematically investigate defects such as 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 Zertifizierungsinstitut, 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

» Accredited testing laboratory according to DIN EN ISO / IEC 17025 for following PV module standards:
  - IEC 61215-1/-2:2016 Terrestrial PV Modules – Design qualification and type approval
  - IEC 61730-1/-2:2016 PV module safety qualification
  - UL 1703 / UL 61730 / UL 61215
  - IEC 61701:2011 Salt mist corrosion testing
  - IEC TS 62804-1:2015 PV Modules – Test methods for the detection of potential-induced degradation (PID)

» Furthermore, we offer:
  - Sand abrasion test
  - Investigation of light and elevated temperature induced degradation (LID / LeTID)
  - Qualification of materials and components
  - Investigation of faults and defects

1 *Accurate and reproducible mechanical load test, illustrated here with a glass-glass module.*
2 *Outdoor test stand to determine the nominal operating temperature of PV modules (NMOT).*

Characterization of Façades and Components

testlab-solarfacades@ise.fraunhofer.de

TestLab
Solar Façades

In TestLab Solar Façades, we characterize transparent, translucent and opaque 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 transmittance, reflectance, g value 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 and polarization-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 *3D-scanning photogoniometer for BSDF measurements.*

2 *Testing the total solar heat gains of a façade element with an integrated solar thermal venetian blind in an outdoor test rig.*

g value and U value testing
Ulrich Amann
Phone +49 761 4588-5142

BIPV, solar control
Dr. Tilmann Kuhn
Phone +49 761 4588-5297

Solar thermal façades
Dr. Christoph Maurer
Phone +49 761 4588-5667

Spectrometry, goniometry, SRI and color measurement
Dr. Helen Rose Wilson
Phone +49 761 4588-5149

Daylighting test rooms
Dr. Bruno Bueno
Phone +49 761 4588-5377

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 ISO 52022, 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

1

Testing of Collectors, Storage Tanks and Systems

testlab-sts@ise.fraunhofer.de

TestLab
Solar Thermal
Systems

The portfolio of TestLab Solar Thermal Systems 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 in the development of solar thermal heating systems.

Approval for the market introduction of PVT collectors often still poses a challenge. For these hybrid collectors, we cooperate with our TestLab PV Modules, which is also accredited, to offer measurements for complete certification of PVT collectors (IEC and ISO). We can also investigate complete heating systems in our laboratories, e. g. the combination of solar solutions with heat pumps, for which we work together with our accredited TestLab Heat Pumps and Chillers.

In our laboratories, the coefficients needed to evaluate products (e. g. tanks) according to the Energy Label (ErP) of the EU are determined. We are also equipped with the only fully accredited test stand in the world for solar air-heating collectors. In addition to many functional tests such as resistance to hail impact or water tightness, we also test the mechanical stability (at -40 °C to +90 °C) of mounting systems, PV modules and solar thermal collectors individually and beyond the test conditions specified in standards, as required by our clients.

Our indoor test stand with a solar simulator achieves high reproducibility, which makes the test stand very attractive especially in the context of product development. With the further development of in situ characterization, new application options have been created at TestLab Solar Thermal Systems for our clients, such as field tests e.g. in district heating networks. Our testing is fundamentally based on the updated version of EN ISO 9806:2018. 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.

In situ measurement
Dr. Korbinian S. Kramer
Phone +49 761 4588-5139

Collectors
Stefan Mehnert
Phone +49 761 4588-5741

Storage tanks, systems
Konstantin Geimer
Phone +49 761 4588-5406

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.*

Measurement and Testing of Heat Pumps

testlab_heatpumps@ise.fraunhofer.de

TestLab Heat Pumps and Chillers offers the most modern technology for developing, measuring and characterizing heat pumps and chillers, as well as their components. The modular test rig concept enables testing of different technologies 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 (based on 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 relative air humidity values between 25 % and 95 %. The laboratory has several conditioning units for water or brine, 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 TestLab Heat Pumps and Chillers was accredited according to ISO / IEC 17025 in 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, shadowgraphy, gas chromatography, scanning vibrometry).

TestLab
Heat Pumps
and Chillers

Ivan Malenković
Phone +49 761 4588-5533
Mobile +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
- The TestLab is authorized to carry out tests for the Heat Pump Keymark
- Tests for Passivhaus-Institut (PHI) certification
- Staff certified according to the F-gas regulation, Class I

1 *Investigating leakage processes in a propane cooling circuit.*

Characterization of Power Electronic Equipment

testlab-pe@ise.fraunhofer.de

TestLab
Power Electronics

The new Multi-Megawatt Laboratory facilities in the Zinkmattenstrasse in Freiburg have significantly extended the power range and the scope of tests offered by the accredited TestLab Power Electronics. Among other aspects, the equipment in the new laboratory enables us to test inverters according to current grid connection guidelines and carry out climatic chamber tests to clients' specifications. We mainly test PV and battery inverters, but also combined heat and power (CHP) plants or loads such as charging points for electromobility. At the new premises, transformers are available to connect the devices to be tested and to check their dynamic behavior in the grid (UVRT and OVRT) up to a power rating of 10 MVA. The Center for Power Electronics and Sustainable Grids (see page 83), newly located in the Zinkmattenstrasse, is also equipped with extensive facilities.

Outside our laboratories, we offer our clients field measurements, for instance of large PV or wind power plants. For this purpose, we have six measurement systems, each with 16 measurement channels, which can be distributed as required in the field and synchronized. Larger generator units (e.g. combined heat and power plants) can be tested with our 4.5 MVA LVRT test container, either directly in the field or in our clients' facilities. Furthermore, a flexibly configurable PV generator with a rated power of 1 MWp is available at our outdoor test field. This PV generator is used particularly for testing inverters under real life conditions.

We measure power-generating units according to international grid feed-in codes (e.g. for Germany, China or Great Britain), and determine the efficiency of power electronic equipment with high accuracy. We also support our clients in modelling power-generating units and PV power stations with their grid connection to evaluate their dynamic stability. 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.

Roland Singer
Phone +49 761 4588-5948

Standards and Specifications

- » Accreditation according to DIN EN ISO / IEC 17025
- » FGW TR3: Determination of the electrical properties of generator systems in the medium-voltage, high-voltage and highest-voltage grid
- » FGW TR4: 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
- » TLPE-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 (P(f)) of bidirectional converters based on the TR3

1 *Programming of PV simulators for inverter testing.*

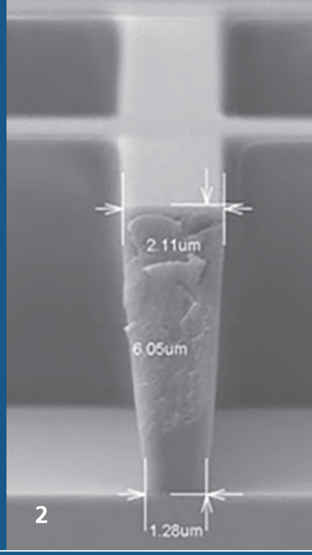
PV-TEC: In-line etching equipment for ozone-based wafer purification and single-sided emitter removal.

R&D INFRASTRUCTURE

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of more than 16 000 m² and extremely modern equipment and facilities are the basis for our competence in research and development. Certified clean-room laboratories with a floor area of 650 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 Optics and Surface Science
- Center for Material Characterization and Durability Analysis
- Center for Heating and Cooling Technologies
- Center for Energy Storage Technologies and Systems
- Center for Electrolysis, Fuel Cells and Synthetic Fuels
- Center for Power Electronics and Sustainable Grids
- 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 being further developed, 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 2018, PV-TEC – Photovoltaic Technology Evaluation Center – was thoroughly modernized after a fire and reopened. In addition, Fraunhofer ISE extended the Center for Power Electronics and Sustainable Grids with new premises in the Zinkmattenstrasse in Freiburg. It is now equipped with extremely modern facilities for the development and testing of power electronic components up to the multi-megawatt range.



Center for High Efficiency Solar Cells

Dr. Martin Hermle | Phone +49 761 4588-5265 | Dr. Frank Dimroth | Phone +49 761 4588-5285

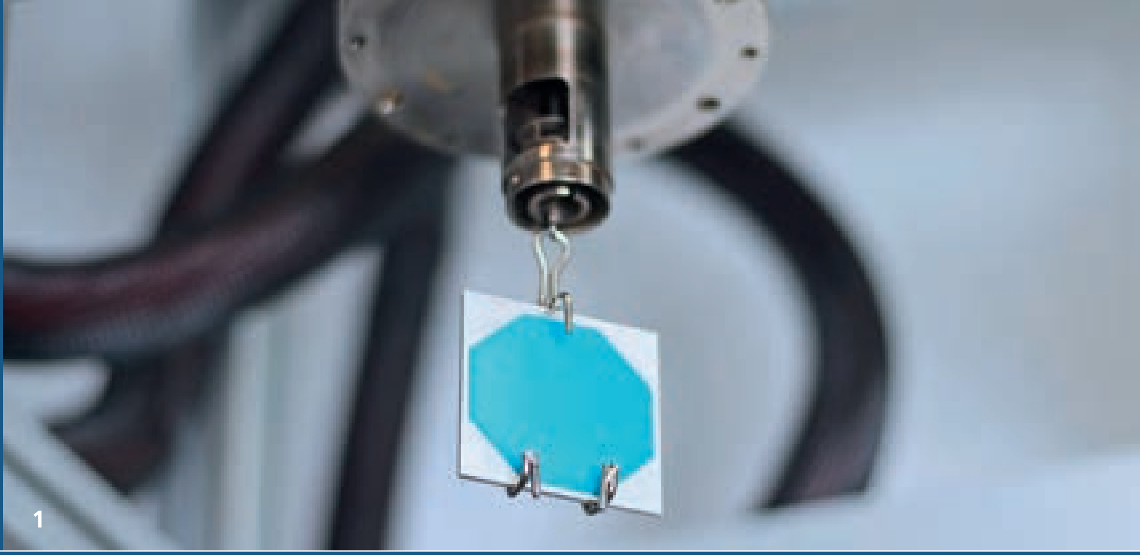
In the "Center for High Efficiency Solar Cells", we develop technology with which highest PV efficiency values can be achieved, and implement it at an internationally leading level. The application possibilities for high efficiency solar cells include not only conventional solar modules but also power supplies for satellites, electric vehicles, autonomous sensors and electronic devices. Fraunhofer ISE holds several world records in the high efficiency solar cell sector, not only the record efficiency value for multicrystalline silicon (22.3 %), but also the absolute efficiency value 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 semiconductor technology for PV, sensors and other application areas can be tested and optimized in extremely modern 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 highest-efficiency silicon-based tandem cells. The combination of silicon with other semiconductor materials is one of the most promising future photovoltaic technologies. With the new laboratory building, 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 *Laser exposure chamber for mask-free, photolithographic structuring of wafers for high efficiency silicon and III-V solar cells.*
2 *Microstructure that was produced by laser exposure of photoresist.*

Technical Facilities

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



Center for Materials 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

The "Center for Material Characterization and Durability Analysis" concentrates the technical competence of Fraunhofer ISE on testing and measuring many diverse materials for active and passive use of solar energy, energy storage and building energy technology.

One particular focus is on the comprehensive determination of material properties. We have special expertise in the investigation of semiconductors, solar cells, photovoltaic modules, thermochemical and porous materials (e. g. zeolites), phase change materials (PCM), heat-transfer fluids, polymers and coatings on glass and metals. In addition, we develop suitable new methods for material analysis, especially non-destructive analytical procedures. We have particular competence in investigating materials under application conditions and different climatic loads, e. g. in differing climatic zones. To estimate the performance and service life of materials in these different applications, we use data from analytical measurements, real operation and accelerated aging tests. In addition, we prepare models to calculate the performance and degradation of materials.

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

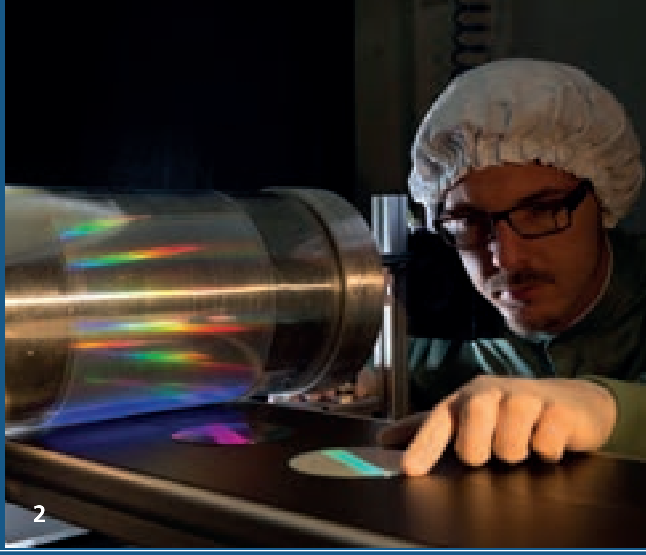
Technical Facilities

Material characterization

- Dilatometer
- Differential scanning calorimeter (10 µl to 10 ml, -90 to 700 °C),
- Modulated temperature calorimeter (up to 100 ml, -10 to 180 °C),
- Plate test rig to determine the temperature-dependent heat capacity and conductivity of planar samples (up to 50 cm x 50 cm)
- Laser-flash and hot-wire equipment to determine temperature-dependent thermal conductivity (-90 °C to 500 °C)
- Lock-in thermography and electroluminescence
- BET porosimetry to determine pore structure and surface area of highly porous materials
- X-ray diffractometry (XRD) to determine crystalline structure
- Confocal Raman microscope with AFM
- Rotational rheometer to determine the rheological properties of materials in the temperature range from -20 °C to 600 °C
- Mass spectrometer to determine temperature-dependent permeation properties of barrier materials
- FT-IR spectrometer with integrating spheres (UV/Vis, IR)
- Photoluminescence, thermographic and electrical methods for spatially resolved and quantitative analysis of silicon material quality and solar cells

Durability Analysis

- Outdoor test sites with comprehensive monitoring in different climatic zones
- Thermal cycling tests of PCM and hydrothermal cycling of adsorbent composite samples
- Testing facilities to investigate degradation of materials and components for semiconductor materials, solar cells and modules



Center for Optics and Surface Science

Dr. Thomas Kroyer | Phone +49 761 4588-5968 | Dr. Benedikt Bläsi | Phone +49 761 4588-5995 |
Anna Heimsath | Phone +49 761 4588-5944

In the "Center for Optics and Surface Science", we develop optically functional surfaces for numerous applications and support developments of our clients. Within coating technology, we work on solutions based on sputtering for thermal use of solar energy, photovoltaics, energy efficiency, 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 or scalability to industrial production scales). Our spectrum of services encompasses feasibility studies, small-series production 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 customized surface structures is the basis for industrial implementation.

In solar cells, photonic structures result in 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 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. We develop and characterize components for concentrating photovoltaics and solar thermal power stations. Parallel to component development, the evaluation of concentrators, soiling analysis and cleaning approaches are subjects of our work. For example, we quantify beam dilation by scattering and shape deformation of reflectors as a contribution to optimization and quality assurance.

1 *Horizontal sputtering unit, equipped with up to 10 planar and double tube cathodes as well as a plasma-etching station.*

2 *Roll-to-plate nano-imprinting equipment to transfer microstructures and nanostructures onto rigid substrates.*

Technical Facilities

- Modern 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, as well as 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
- Plasma-etching equipment to transfer imprinted structures onto non-polymer materials
- Characterization of electrical, optical, microstructural and chemical properties: Fourier spectrometry, scanning electron microscopy (SEM), atomic force microscopy (AFM), 3D scanning goniometry to quantify scattering and beam dilation (VLABS: very low angle beam spread)
- Deflectometry to determine shape deformation of moulding tools and concentrator optics

Center for Heating and Cooling Technologies

Dr. Peter Schossig | Phone +49 761 4588-5130

In the “Center for Heating and Cooling Technologies”, Fraunhofer ISE concentrates its technical competence to test and characterize many types of equipment and components for use in building technical services. With extensive and modular infrastructure, we cover different power categories and investigate diverse aspects of equipment and its components. We specialize in:

» Investigation and evaluation of novel heat exchangers for ventilation and air-conditioning technology, adsorption and cooling technology
» Investigation and evaluation of natural refrigerants
» Investigation and evaluation of cooling circuit components (compressors, valves)
» Tools and methods to develop safety concepts

For example, we analyze and evaluate the heat transfer and pressure loss in typical structural segments and full-scale heat exchangers with different fluids. Compressors, heat pumps and chillers are measured according to different standards and sets of guidelines.

One thematic focus is on the development and evaluation of components for natural refrigerants such as propane. Our entire laboratory is thus equipped for work with flammable refrigerants and allows us to develop and optimize components for propane cooling circuits. This applies both to test stands to measure compressors and heat exchangers with reduced amounts of refrigerant and also to climatic chambers to measure the performance of complete units according to the relevant standards.

1 *One of the three air-handling units.*

Technical Facilities

» Test stands to measure the dynamic / stationary boiling and adsorption characteristics of water at low pressure in structural segments and heat exchangers
» Test stands to measure heat exchangers to air operating with different fluids (water, brine, refrigerants)
» Three air-handling units for volume flow rates from 80 m^3/h to 5000 m^3/h, heating power from 2 to 50 kW, cooling power from 2 to 15 kW, temperature range from -15 °C to +50 °C
» Test stands to determine refrigerant distribution
» Test stand for compressor testing
» Calorimetric double climatic chamber to test equipment with up to 100 kW heating or cooling power at temperatures from -25 °C to +50 °C and relative air humidity values from 25 % to 95 %
» Particle image velocimetry (PIV)
» Laser Doppler anemometry (LDA shadowgraphy)
» Vibrometry

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 concentrating particularly on battery technology. We work with novel materials, develop 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 bank 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, cell and system levels. We carry out comprehensive testing and checking of batteries, including performance and aging investigations (calendric, 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 storage and storage system components (charge controllers, energy management systems, etc.).

We offer comprehensive quality control of electrical and thermal storage systems. The applied methods range from simulation-based system design and optimization, through system tests in the laboratory and in the field, to system monitoring. In the thermal storage field, this encompasses storage units both for heat and for cooling energy.

1 *Development and testing 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 chemistry
- 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 systems for energy-relevant analysis of thermal storage units in operation
- Test facility to characterize storage units according to EN 12977-3

Center for Electrolysis, Fuel Cells and Synthetic Fuels

Dr. Christopher Hebling | Phone +49 761 4588-5195

In the "Center for Electrolysis, Fuel Cells 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 and Power-to-Chemicals.

1 *Differential test cell to characterize fuel cell components, a development of Fraunhofer ISE together with balticFuelCells GmbH.*

Technical Facilities

PEM Electrolysis

» Two test stands to characterize electrolyzer 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 electrolyzer cells under 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

1

2

Center for Power Electronics and Sustainable Grids

Dr. Olivier Stalter | Phone +49 761 4588-5467

With this center, Fraunhofer ISE can offer an unique infrastructure. Thanks to our own high-voltage connection, we can study inverters and their effect on the electricity grid in the multi-megawatt range and test their conformity with the most recent grid-connection guidelines (see page 75). The development of innovative power electronics for low voltage and medium voltage is another focus of our activities. Furthermore, the center offers extensive access to intelligently interconnected energy systems. With this, we can test both individual solutions and complex systems in realistic surroundings. Our research activities there concentrate on digitalization and intelligent operation management, as well as sustainable grids and stronger intersectoral coupling.

1 *Smart-Energy Lab at Fraunhofer ISE.*

2 *New premises in the Zinkmattenstrasse, Freiburg.*

Technical Facilities

Power Converters Lab

- Bidirectional DC sources (up to 1000 V / 600 A)
- Machine emulator (160 kVA) and grid simulator (30 kW)
- Load resistance for DC and AC voltage (200 kW)
- Programmable non-linear loads (3-phase, 230 V / 16 A)
- High-resolution, broadband oscilloscopes and sensor heads
- Multi-channel systems and accurate power measurement
- Measurement EMC disturbance (up to 200 A_{AC} / 400 A_{DC})
- High-resolution, high-frequency thermography camera
- Accurate inductivity measurement instrument and impedance analyzer
- Multi-gate vector grid analyzer
- Hardware-in-the-loop (HIL) system from OPAL-RT
- Vapor-phase reflow soldering system
- Fine-placer microscope soldering station
- Test stand to characterize SiC/GaN semiconductors

Multi-Megawatt Lab

- In-house connection to 110 kV grid (20 kV / 40 MVA transformer)
- Highly accurate, broadband measurement up to 110 kV
- Test fields up to 7 MVA and from 260 V to 1000 V
- PV simulator (2000 V / 1.4 MW)
- Bidirectional battery simulator (750 V / 1 MW)
- High-dynamic grid simulator with reverse feedback (1 MVA)
- UVRT and OVRT test unit for test specimens up to 10 MVA
- Mobile UVRT test container (4.5 MVA)
- Inductive and capacitive loads (7 MVAr)
- Anti-islanding test stand (400 kVA)
- Climatic chambers for large equipment (-30 °C to +80 °C)
- High-accuracy power measurement (1000 V / 5000 A)

Medium Voltage Lab

- Test field with medium-voltage connection (20 kV / 20 MVA)
- Medium-voltage DC source (40 kV / 660 kW)
- Medium-voltage resistor (20 kV / 1 MW)
- Medium-voltage transformer (3 to 30 kV / 2.5 MVA)
- Railway transformer (16.6 Hz / 15 kV / 200 kVA)
- Semiconductor test stands to characterize leakage currents (to 30 kV), avalanche effects (to 4 kV / 100 A) and switching losses (to 20 kV / 1000 A

Smart Energy Lab

- Simulator for variable, electrical load profiles
- PV simulator for dynamic IV characteristics
- HIL system to model thermoelectric load profiles
- Test stand for battery management systems
- Grid-connected charging stations for electric vehicles
- IT-monitoring platforms for living laboratories and field tests

SiM-TEC – Silicon Material Technology Evaluation Center

Dr. Stephan Riepe | Phone +49 761 4588-5636

SiM-TEC is the research center at Fraunhofer ISE that develops new technologies to produce silicon wafers for photovoltaics and evaluates the materials used. For the production of multicrystalline wafers, the work in SiM-TEC encompasses the evaluation of new feedstock materials, further development of oriented solidification of multicrystalline blocks and the production of wafers based on sawing processes. In the kerfless wafering sector, we investigate processes for electro-chemical porosification and the deposition of silicon with atmospheric-pressure epitaxy in high-throughput processes. We accompany all of the listed technological steps with numerous analytical options and simulation.

To minimize the introduction of impurities during the production of multicrystalline wafers, we are studying crucible systems and coatings with greater purity. Crystallization occurs as oriented solidification according to the vertical gradient freeze (VGF) process, with a focus on developing high quality wafers through processes with and without a seed crystal, as well as improving the material homogeneity and throughput by feeding silicon during crystallization.

As a further technological focus, we are developing the epitaxy of extremely pure silicon material by chemical vapor deposition (CVD) in a continuous process. This is applied e. g. to grow epitaxial wafers (see page 29). We are equipped with an in-line etching facility which can carry out several full-area (156 mm x 156 mm) etching processes in electrically separate baths for the electro-chemical processing of silicon wafers.

1 *"Multicrystallizer VGF632" crystallization unit for oriented solidification of silicon blocks.*

Technical Facilities

- Crystallization unit (PVA Tepla VGF 623 Multicrystallizer)
- Multi-wire saw (Meyer Burger DS 265)
- Column inspection equipment (Intego Orion Super High Resolution)
- Block characterization facility (Semilab WT-2000D)
- Inline porosification system (IporSi)
- Continuous epitaxial unit (ConCVD)
- Continuous epitaxial unit (ProConCVD)
- Optical film thickness scanner (CyberTechnologies CT-250T)

PV-TEC – Photovoltaic Technology Evaluation Center

Dr. Ralf Preu | Phone +49 761 4588-5260

The PV-TEC – Photovoltaic Technology Evaluation Center serves to fill the gap between laboratory research and industrial application. After a serious laboratory fire in February 2017, the large-scale laboratory was not only opened again in July 2018, but was also extensively modernized. Cutting-edge processing and characterization equipment is available for the development of silicon solar cells.

We focus on 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

1 *Coating system in PV-TEC.*

2 *New screen-printing line in PV-TEC.*

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

High-Efficiency, Industrially Relevant Silicon Solar Cells

In PV-TEC, we are working on further development and optimization of the standard process to produce silicon solar cells, and extend this e.g. with 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. We are also able to use partly processed solar cells in all industrially widespread formats and to evaluate selected processes and processing sequences. One current focus of work is on the PERC solar cell (passivated emitter and rear cell), which 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 stage in development.

Technical Facilities

PV-TEC front-end

» Automated wafer inspection system
» Wet-chemical batch and inline equipment for texturing, purification and single-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 films, as well as 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

» Fully automated laser and printing equipment for structuring and metallization
» High-throughput rotary printing system
» Multi-nozzle dispensing unit for fine linear metal contacts on the front surface
» Printing process development with diverse printing technology
» Laser process development laboratory with different radiation sources
» Innovative in-line furnaces for contact formation and regeneration

Module-TEC – Module Technology Evaluation Center

Dr. Holger Neuhaus | Phone +49 761 4588-5825

Industrial production equipment and multi-functional analytical tools in Module-TEC offer extensive opportunities to develop connection and encapsulation technologies for PV modules. The processing of innovative materials can be tested, and sample modules and small series for test and demonstration purposes can be produced. Depending on the research question and the stage of development, modules are produced from single-cell to full-scale dimensions.

In addition to the usual three to five ribbons per cell, also multi-wire, structured connectors or conductive backsheets are processed as cell connectors. Alternatively, we can produce module strings in a shingled configuration, with the cell edges overlapping. Not only full-size cells (app. 156 mm x 156 mm) can be connected to form strings, but also half cells and smaller segments. Our stringers apply infrared radiation, induction or hot air to heat the joints. In addition to commercially widespread soldering, solar cells can be connected by electrically conductive adhesives (ECA), which are applied in a fully automated process. This innovative concept of adhesive connection is particularly suitable for temperature-sensitive high-efficiency cells such as heterojunction solar cells, for very thin solar cells and for shingled connection.

Modules in glass-backsheet or glass-glass configuration are encapsulated in our laminators. We are able to fabricate three-dimensional laminates as well as edge-sealed glass-glass modules without lamination (TPedge).

Our customers use the services of Module-TEC when integrating new materials and high-efficiency cells into modules and for detailed analysis and optimization of the module efficiency. A further focus is the development of application-specific modules, e. g. for building integration (BIPV) and vehicle integration (VIPV).

1 *Industrial stringer for connecting solar cells to form modules.*
2 *Shingled connection of solar cells with ECA on structured Slimline EVA film.*

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 contacts 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, dispensing processes, pick-and-place tasks and controlled UV curing
- 3D X-ray computer tomography
- Industrial scale laminators for encapsulating solar cells, adapted for thick structures and spherically curved modules
- Equipment to produce polished metallographic specimens and polished cross-sections of 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 | Phone +49 761 4588-5470

Our activities on concentrator module development are merged in Con-TEC. Here, we develop novel generations of PV modules with high and low concentration factors, and test components and production processes. Further topics 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 optical silicone to produce optics, for optical coupling of secondary optics or to encapsulate solar cells.

A further research focus is on investigating the reliability of assemblies. In concentrating photovoltaics, particularly the thermal interconnection of the solar cell to the substrate is decisive, as the concentrated irradiance 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 *Pick&place of solar cell assemblies onto the bottom glass plate.*

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 up to 300 x 300 mm² with void-free connection
- Soldering without flux, applying formic acid or activation with forming gas
- Bonder for thick and thin gold and aluminium wires
- Equipment to align primary optics with respect 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)
- Peeling and shear tester (Dage Series 4000)
- Climatic chambers for temperature conditioning or thermal cycling, with or without additional loads due to elevated air humidity; testing of solar cell components with applied reverse voltage and irradiance of optical components or encapsulation materials with concentrated UV radiation

EDITORIAL NOTES

Editorial Team
Christina Lotz, Karin Schneider (Editor-in-chief)

Editorial Address
Fraunhofer Institute for
Solar Energy Systems ISE
Press and Public Relations
Heidenhofstrasse 2
79110 Freiburg, Germany
Phone +49 761 4588-5150
Fax +49 761 4588-9342
info@ise.fraunhofer.de
www.ise.fraunhofer.de

www.ise.fraunhofer.de/en/press-and-media

We keep you up to date here
www.ise.fraunhofer.de
blog.innovation4e.de
Twitter: FraunhoferISE
Facebook FraunhoferISE
https://www.youtube.com/c/FraunhoferISE-official

Translation from German
Dr. Helen Rose Wilson

Layout and Printing
netsyn, Joachim Würger, Freiburg, Germany
www.netsyn.de

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Photographers

Auslöser Fotodesign Kai-Uwe Wuttke: Page 3
Simon Braungardt: Pages 46/47
Michael Eckmann: Pages 29, 43, 73
Markus Feifel: Page 34
Joscha Feuerstein: Pages 56, 58, 82
Guido Kirsch: Page 13
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64 Fig. 2, 75, 76, 77 Fig.1, 79 Fig. 2, 81, 83, 85, 86 Fig.1, 87
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Gesche Wilhelmi: Page 66 Fig. 2

EVENTS IN 2019

WITH PARTICIPATION OF FRAUNHOFER ISE

BAU Munich
Munich, Germany, 14.–19.01.2019

Zukünftige Stromnetze für Erneuerbare Energien
Berlin, Germany, 30.–31.01.2019

E-World
Essen, Germany, 05.–07.02.2019

BAMB-CIRCPATH 2019
Brussels, Belgium, 05.–07.02.2019

PV-Module Forum
Cologne, Germany, 12.02.2019

IEWT TU Vienna
Vienna, Austria, 13.–15.02.2019

ISEC 2019
Pune, India, 14.–16.02.2019

SiliconFOREST
Falkau, Germany, 24.–27.02.2019

Internationale Sanitär- und Heizungsmesse (ISH)
Frankfurt, Germany, 11.–15.03.2019

Energy Storage Europe
Düsseldorf, Germany 12.–14.03.2019

Forum Bauwerk-integrierte Photovoltaik
Kloster Banz, Bad Staffelstein, Germany 18.03.2019

Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, Germany 19.–21.03.2019

15th International Conference on Concentrator Photovoltaic Systems
Fes, Morocco, 25.–27.03.2019

Hannover Messe Industrie
Hanover, Germany, 01.–05.04.2019

Solarex
Istanbul, Turkey, 04.–06.04.2019

Silicon PV
Leuven, Belgium, 08.–11.04.2019

Intersolar Europe / Electrical Energy Storage
Munich, Germany, 15.–17.05.2019

EVS 32
Lyon, France, 19.–22.05.2019

Berliner Energietage
Berlin, Germany, 20.–22.05.2019

Symposium Thermische Solarenergie
Kloster Banz, Bad Staffelstein, Germany, 21.–23.05.2019

Urban Future Global Conference
Oslo, Norway, 22.–24.05.2019

Hydrogen Fuel Cell Summit
Vancouver, Canada, 22.–23.05.2019

13th REHVA World Congress CLIMA 2019
Bukarest, Romania, 26.–29.05.2019

9th SOPHIA Workshop PV-Module Reliability 2019
Graz, Austria, 28.–29.05.2019

13th SNEC PV POWER EXPO *Shanghai, China, 03.–05.06.2019*

International Conference on Electricity Distribution (CIRED)
Madrid, Spain, 03.–06.06.2019

International Conference on Electrolysis
Loen, Norway, 09.–13.06.2019

46th IEEE Photovoltaic Specialists Conference
Chicago, USA, 16.–21.06.2019

Electrical Energy Storage North America
San Francisco, USA, 09.–11.07.2019

16th IAEE European Conference
Ljubljana, Slovenia, 25.–28.08.2019

16th IPSA International Conference and Exhibition, Building Simulation 2019
Rome, Italy, 02.–04.09.2019

CISBAT 2019
EPFL Lausanne, Switzerland, 04.– 06.09.2019

35th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)
Marseille, France, 09.–13.09.2019

f-cell 2019
Stuttgart, Germany, 10.–11.09.2019

25th SolarPaces 2019
Daegu, South Korea, 01.–04.10.2019

Building Simulation Conference 2019
Rome, Italy, 02.–04.10.2019

5th International Symposium on Innovative Materials and Processes in Energy Systems, IMPRES2019
Kanazawa, Japan, 20.–23.10.2019

Advanced Building Skins
28.–29.10.2019, Bern, Switzerland

Council on Tall Buildings and Urban Habitat (CTBUH) 2019
Chicago, USA, 28.10.–2.11.2019