Fraunhofer
ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Annual Report 2019/20

Detail of a new stele at the main entrance to Fraunhofer ISE, which displays different high-efficient BIPV modules with the patented MorphoColor® layer. The MorphoColor® layer consists of a photonic structure, in which an interference coating is combined with a geometrically structured substrate such that a narrow band reflectance peak results. It reflects only one specific color and transmits almost all of the remaining sunlight. The design of the layer was inspired by the colored surface of the morpho butterfly's wings. Because the reflectance peak is so narrow, the colored module retains 90 % of the PV efficiency of a comparable black module. As a result, both a high electricity yield and aesthetic design options become feasible for PV façades. The stele thus demonstrates how innovative technologies can contribute to make solar-activated building envelopes a common feature that can be used to design CO_2-neutral and architecturally attractive buildings.

Annual Report
2019/20

FOREWORD

Climate change and thus the German energy transformation have reached a new dimension of public awareness, not least due to the "Fridays for Future" movement. Steps for political action are becoming more concrete with the "Climate Package" presented by the German Federal Government late in 2019. The necessity and urgency of political action have been confirmed by the most recent results reported by the IPCC, among others. Consequently, we have set a 95 % reduction in greenhouse gas emission by 2050, relative to 1990 levels, as the minimum target for the new edition of the study by Fraunhofer ISE, "Paths to a Climate-Neutral Energy System – The German Energy Transformation in its Social Context" ("Wege zu einem klimaneutralen Energiesystem – Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen"). The energy transformation requires technologies and systemic solutions which we are researching and developing at Fraunhofer ISE. It is thus evident that we can look back, in this annual report, on a successful year with regard to both funding and growth.

Photovoltaics is a major pillar of the energy transformation. This conclusion has been reached in all relevant studies. The required expansion in Germany to at least 500 GW will occur not only on roofs and open land areas but also in the built environment. We are convinced that integration of photovoltaics into a wide range of application areas is feasible to a much greater extent than the current status. We have expressed this with our strategic research and development activity on "Integrated Photovoltaics" (pages 18, 39, 49).

Heat pumps also assume a key role in the energy transformation. We have been working for years on the entire value chain from materials up to heat pump tests and monitoring in the field. A most recent result of our work is the development of a heat pump prototype with the climate-friendly refrigerant, propane, for indoor installation in residential buildings (page 46).

Hydrogen technology is gaining momentum at present, both internationally and in Germany. Fraunhofer ISE has a key position in activities of the Fraunhofer-Gesellschaft regarding hydrogen technology and was heavily involved in preparing the hydrogen road map of the Fraunhofer-Gesellschaft, which was presented to several Federal Ministries last fall.

The symposium on the "Business Model for the Energy Transformation", an expert dialogue which was initiated by Fraunhofer IEE in 2015, will now be run jointly on an annual basis in Berlin by the core institutes – Fraunhofer IEE, Fraunhofer ISI and Fraunhofer ISE – of the Fraunhofer Cluster of Excellence on "Integrated Energy Systems CINES", which was newly founded in 2019. Drawing on a well-founded, model-based energy systems analysis, the cluster is supporting the technically and economically optimized development of a CO_2-emission-free energy system, in which heat, electricity and transport are coupled. Work is proceeding within the cluster on the necessary strategies, components and technologies.

In Freiburg, Fraunhofer ISE organized a symposium on "Dimensions of the Energy Transformation" in October, which centered on a trans-disciplinary panel discussion of experts from different fields. The event marked the occasion of Prof. Hans-Martin Henning's 60th birthday.

The Fraunhofer-Gesellschaft itself turned 70 last year. The five Institutes located in Freiburg celebrated with a festival in the inner city last fall. Around 5000 visitors gained hands-on experience of Fraunhofer research and enjoyed an entertaining program, including a laser show.

2019 brought an extension to the infrastructure of the Institute as well as structural and personnel changes. One highlight in summer was the official opening of our new "Center for Power Electronics and Sustainable Grids", which is located in the Zinkmattenstrasse in Freiburg. With its own 110 kV high-voltage connection and power of 40 MVA, this laboratory

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

center is equipped with an internationally unique research infrastructure. It is well prepared to meet the raised expectations on power electronics as a key technology of the energy transformation (page 60).

Regrettably, due to difficult economic boundary conditions, we had to close the Fraunhofer Center for Sustainable Energy CSE in Boston, which had been founded in 2008. At this point, we sincerely thank Dr. Christian Höpfner, the Director of Fraunhofer CSE, for his exceptional contribution and are pleased to know that the staff can continue their work locally at other institutions. Also, the external branch operated jointly by Fraunhofer ISE and Fraunhofer IISB in Freiberg, the Technology Center for Semiconductor Materials (THM), experienced a decisive change. We transferred the wafer processing from the previous location in Freiberg to the Center for Silicon Photovoltaics (CSP) in Halle; the activities in Freiberg are being terminated. Here also, our gratitude is extended to the local staff for their excellent work.

Increasing the number of female scientists at Fraunhofer ISE and expanding the career opportunities for women is an important goal for us. We are thus very pleased that we were able to support our Equal Opportunity Representative in starting two attractive internal programs to encourage female scientists in 2019.

Two changes occurred at the Division leadership level last year. Dr. Alexandra Heßling, Head of the Business Administration Division, left Fraunhofer ISE because she moved away from Freiburg for personal reasons. During her short time at the Institute, she had set much in motion, for which we thank her. The process of filling the vacant position is currently underway. Dr. Olivier Stalter, one of the Heads of the Division for Energy Technologies and Systems and Head of the Department for Power Electronics, Grids and Intelligent Systems, left the Institute for a career change. We thank him for his excellent work. After an intensive selection process, we greet Prof. Christof Wittwer as the new Head of Division in this function and look forward to further collaboration with him as a long-term member of the Institute staff.

Dr. Christopher Hebling, who is another of the Heads of the Division for Energy Technologies and Systems and Head of the Department for Hydrogen Technologies, was awarded an honorary professorship at the University of Cape Town in South Africa. We extend congratulations to him on this appointment. Similarly we congratulate Dr. Elke Lorenz, who came to Fraunhofer ISE as a candidate of the Fraunhofer Attract Program with a research focus on energy meteorology, on receiving her habilitation (postdoctoral lecturing qualification) at the University of Oldenburg.

And last but not least in this list of academic recognition, we are pleased to report that Dr. Andreas Bett has been appointed to the Chair of "Solare Energie – Materialien und Technologien" ("Solar Energy – Materials and Technologies") in the Faculty of Mathematics and Physics at the University of Freiburg.

We extend our sincere gratitude to our Board of Trustees, auditors, scholarship donors, contact persons and funding sources in the Ministries at the Federal and State levels and to all of our project partners for support and funding of Fraunhofer ISE as well as good collaboration. We look forward to further cooperation toward rapidly transforming the energy system in Germany and globally, work that is so necessary to ensure that our planet continues to be a good place to live.

Prof. Hans-Martin Henning Prof. Andreas Bett

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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:

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

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).

Institute Directors

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

Heads of Photovoltaics Division

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

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Dr. Peter Schossig | Phone +49 761 4588-5130
Prof. Christof Wittwer | Phone +49 761 4588-5115

Business Administration

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Phone +49 761 4588-0

Facility Management

Jochen Vetter | Phone +49 761 4588-5214

Communications

Karin Schneider | 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 2019).

Chairman
Burkhard Holder
VDE Renewables GmbH | Alzenau

Members

Dr. Klaus Bonhoff
German Federal Ministry of Transport and Digital Infrastructure (BMVI) | Berlin | formerly NOW GmbH, Nationale Organisation für Wasserstoff- und Brennstoffzellentechnologie | Berlin

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

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

Daniel Etschmann
Kreditanstalt für Wiederaufbau | Frankfurt

Günther Leßnerkraus
Ministerium für Wirtschaft, Arbeit und Wohnungsbau, Baden-Württemberg | Stuttgart

Sylvère Leu
Meyer Burger Technology AG | Gwatt | Switzerland

Helge Pols
German Federal Ministry of Transport and Digital Infrastructure (BMVI) | Berlin

Dr. Norbert Pralle
Ed. Züblin AG | Stuttgart

Dr. Klaus-Dieter Rasch
Former manager of AZUR SPACE Solar Power GmbH | Heilbronn

Prof. Leonhard Reindl
University of Freiburg | Freiburg

Dr. Norbert Schiedeck
Vaillant Group | Remscheid

Gabriele Schmiedel
Siemens AG | Erlangen

Thomas Speidel
ads-tec GmbH | Nürtingen

Prof. Frithjof Staiß
Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) | Stuttgart

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 1269 (870 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, 89 % 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 9001:2015.

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 – "Photovoltaics" and "Energy Technologies and Systems" – address five market-oriented business areas:

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

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 Heat Pumps and Chillers
- TestLab Power Electronics

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

R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of more than 17 000 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 seven Laboratory Centers and four production-relevant Technological Evaluation Centers:

- Center for High Efficiency Solar Cells
- 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 Fuel Cells, Electrolysis 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

1 *Main building of Fraunhofer ISE in Freiburg.*

EXTERNAL BRANCHES, COOPERATION, NETWORKS

In addition to its headquarters in Freiburg, Fraunhofer ISE has two external branches – one of them operated jointly with the Fraunhofer Institute for Microstructure of Materials and Systems IMWS in Halle. The Institute is directly involved in international collaboration in South America and holds Memoranda of Understanding with 57 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 Research Alliance (EERA), 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 of Fraunhofer ISE

- 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

International Cooperation

- Fraunhofer Chile Research – Centro para Tecnologías en Energía Solar (FCR-CSET), Santiago, Chile: solar generation of electricity, thermal solar energy, 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 the Digital Context, Energy Systems and Energy in the Urban Context.

Further Networking within the Fraunhofer-Gesellschaft

- Fraunhofer Alliances: Batteries, Building, Space, Water Systems (SysWasser)
- Cluster of Excellence Integrated Energy Systems CINES
- Fraunhofer Electromobility Systems Research
- Fraunhofer Group: Materials, Components MATERIALS
- Fraunhofer Networks for 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 is operated jointly by 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 *The Centro para Tecnologías en Energía Solar (FCR-CSET) in Santiago de Chile focuses on solar generation of electricity, thermal solar energy, water purification and process heat.*

PRIZES AND AWARDS

Dr. Michael Hermann | "FASSADENPIXEL – Autonom kletternde Solarernteroboter" (Autonomously Climbing Solar Harvesting Robots) | 3rd place | Competition of ideas: "What is your Moonshot Vision?" | Fraunhofer-Gesellschaft | 26.–27.02.2019 | Munich | Germany

Stefan Brachmann | Responsibility for apprenticeships | Fraunhofer Apprenticeship Supervision Prize 2018 | Fraunhofer-Gesellschaft | 01.03.2019 | Freiburg | Germany

Sönke Rogalla, Sebastian Schlick, Florian Ackermann | 1st Poster Prize | "Impedanzspektroskopie von Wechselrichtern – Ein neues Verfahren zur Bestimmung von Oberschwingungen" (Impedance Spectroscopy of Inverters – a new Procedure to Determine Harmonics) | Symposium Photovoltaische Solarenergie | 19.–21.03.2019 | Bad Staffelstein | Germany

Sebastian Tepner | Best Paper Award | "Improving Wall Slip Behavior on Screen Emulsions for Fine Line Screen Printing" | SiliconPV 2019 | 11.04.2019 | Leuven | Belgium

Dr. Frank Feldmann | 2nd place, Best Paper Award | "Studying Dopant Diffusion from Poly-Si Passivating Contacts" | SiliconPV 2019 | 11.04.2019 | Leuven | Belgium

Dr. Tim Niewelt, Regina Post, Dr. Florian Schindler, Dr. Wolfram Kwapil, Dr. Martin C. Schubert | Poster Award 2019 | "Investigation of LeTID Where We Can Control it – Application of FZ Silicon for Defect Studies" | SiliconPV 2019 | 10.04.2019 | Leuven | Belgium

Matthias Haid, Cornelius Armbruster, David Derix, Christian Schöner, Dr. Henning Helmers | Paper Award | "5W Optical Power Link with Generic Voltage Output and Modulated Data Signal" | OWPT2019 | 23.–25.04.2019 | Yokohama | Japan

Monika Bosilj | Lecture "Sustainabile Hydrothermal Carbons for Biorefinery-related Catalysis" | Session "Young Scientist Forum" | World Chemistry Forum | 22.–24.05.2019 | Barcelona | Spain

Dr. Korbinian Kramer | Mission Innovation Champion | International Conference of Ministers for the Environment of the Mission Innovation Initiative | 28.04.2019 | Vancouver | Canada

Nikolas Köppel | TUM Energy Best Poster Award 2019 | Poster "Environmental Performance of Synthetic Fuel" | Technical University of Munich Colloquium "Shaping a Sustainable Energy Future" | 01.08.2019 | Munich | Germany

Bernd Steinhauser | Best Poster Award, Silicon PV | "Life(time) at the Limits – Very High Lifetimes in Crystalline Silicon Measured by Photoconductance and Photoluminescence" | EU-PVSEC 2019 | 13.09.2019 | Marseille | France

Christoph Luderer | Best Poster Award, Silicon PV | "Transport Losses at the TCO / a-Si:H / c-Si Heterojunction: Influence of Different Layers and Annealing" | EU-PVSEC 2019 | 13.09.2019 | Marseille | France

Laura Mundt | Eva-Mayr-Stihl Young Researchers' Prize 2019 of the University of Freiburg | 23.10.2019 | Freiburg | Germany

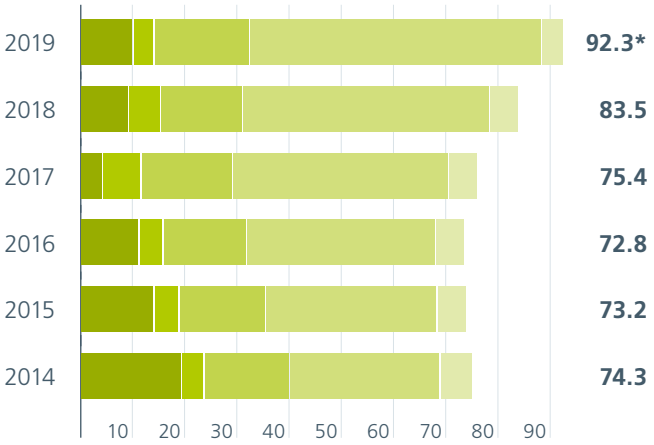
Jan Wienold, Jens Christoffersen | Best Research Paper 1998–2007 | "Evaluation Methods and Development of a new Glare Prediction Model for Daylight Environment with the Use of CCD Cameras" | Energy and Buildings Journal

Marco Glatz |"Honoring the Best in 2019" Fraunhofer-Gesellschaft | Bachelor thesis in a dual studies course "Charakterisierung und Weiterentwicklung von Diffusionsprozessen zur Ausbildung Bor-dotierter Emitter in n-Typ Siliciumsolarzellen" (Characterization and Further Development of Diffusion Processes to Form Boron-Doped Emitters in n-Type Silicon Solar Cells) | 25.–27.11.2019 | Munich | Germany

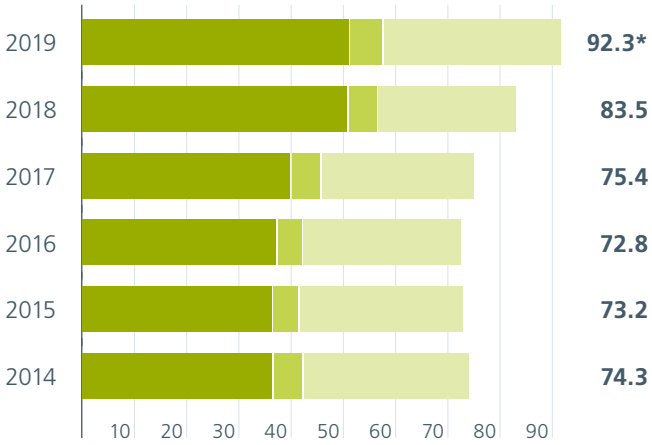
1 *Dr. Korbinian Kramer was awarded "Mission Innovation Champion" at the International Conference of Ministers for the Environment in Vancouver.*

THE INSTITUTE IN FIGURES

Income in million euros**

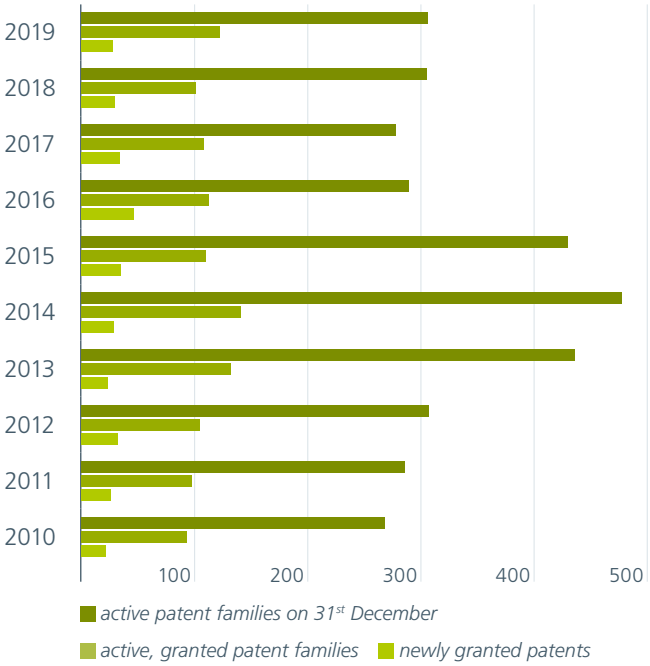


Expenditure in million euros**



** preliminary **without investments – the total budget 2019 (incl. investments) totalled 102.6 million euros.*

Patents

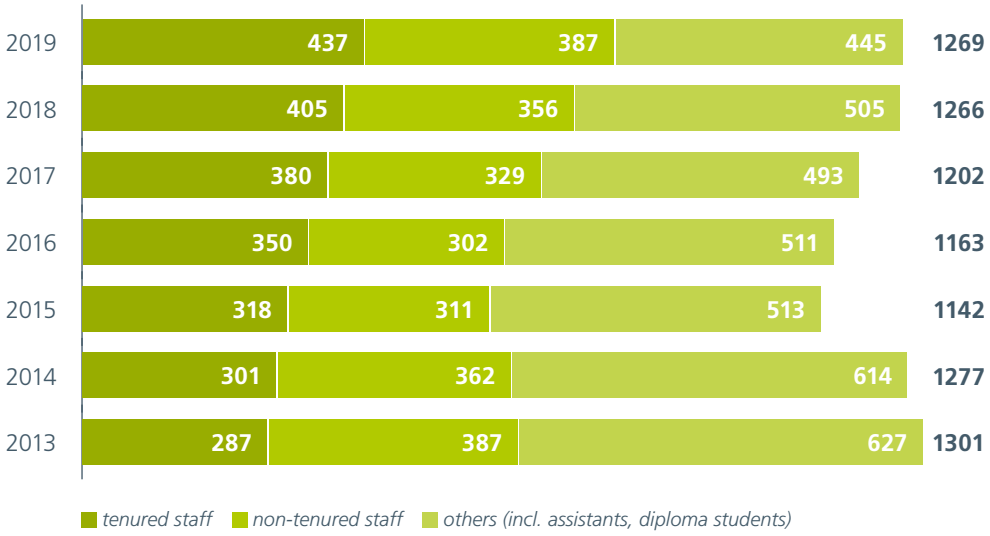


Lecture Courses and Seminars

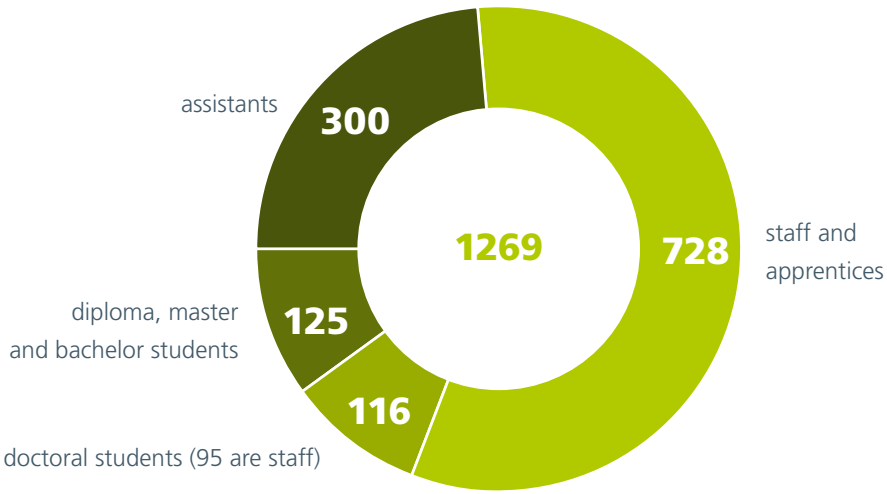
57	University of Freiburg
5	Offenburg University of Applied Sciences
1	KIT Karlsruhe Institute of Technology
1	Martin Luther University Halle-Wittenberg
1	University of Koblenz-Landau
2	TH Georg Agricola Bochum
1	Ruhr University of Bochum

48 Scientists of Fraunhofer ISE give regular lectures at universities in addition to their research work.

Personnel



Personnel 2019



DOCTORAL THESES AND PROFESSORSHIPS

Phillipp Bendix
"Beschichtung von Sorptionsmaterialien" (Coating of Sorption Materials) | University of Freiburg | 2019

Gregor Bern
"Bildverarbeitendes Regelungssystem für Heliostatenfelder" (Image-Processing Control System for Heliostat Arrays) | Karlsruhe Institute of Technology (KIT) | 2019

Andreas Büchler
"Interface Study on Laser-Structured Plated Contacts for Silicon Solar Cells" | University of Freiburg | 2019

Verena Fluri
"Wirtschaftlichkeit von zukünftigen Geschäftsmodellen dezentraler Stromspeicher" (Economic Viability of Future Business Models for Distributed Electricity Storage) | Europa-Universität Flensburg | 2019

Hannes Fugmann
"Optimierter Wärmeübergang und Druckverlust in der Wärmeübertragung durch Verwendung von Drahtstrukturen" (Optimized Heat-Transfer Interface and Pressure Loss in Heat Transfer by Application of Wire Structures) | Karlsruhe Institute of Technology (KIT) | 2019

Georg Hagelstein
"Untersuchung zum Kristallisationsverhalten in n-Octadecan-Wasser-Dispersionen" (Investigation of Crystallization Behavior in n-Octadecane Water Dispersions) | University of Freiburg | 2019

Patricia Krenckel
"Analyse struktureller Defekte in Siliciumkristallen aus gerichteter Erstarrung mit Keimvorgabe" (Analysis of Structural Defects in Silicon Crystals from Oriented Solidification with Seeding Precursors) | University of Constance | 2019

Harry Kummer
"Adsorptive Coating Systems based on Hybrid Siloxane Binders for Heat Transformation Applications" | University of Leipzig | 2019

Mathias List
"Advanced Electrical and Optical Characterization of Recombination in Organic Solar Cells" | University of Freiburg | 2019

Thorsten Müller-Eping
"Tensordekomposition qualitativer Modelle zur Fehlererkennung – Anwendung in der Gebäudeautomation" (Tensor Decomposition of Qualitative Fault-Detection Models – Applications in Building Automation) | Karlsruhe Institute of Technology (KIT) | 2019

Laura Mundt
"High-Resolution Analysis of Perovskite Absorbers in Photovoltaics" | University of Freiburg | 2019

Markus Niemeyer
"Entwicklung von metamorphen Mehrfachsolarzellen mit vier pn-Übergängen auf einem Germaniumsubstrat" (Development of Metamorphous Multi-Junction Solar cells with four pn Junctions on a Germanium Substrate) | Technical University of Ilmenau | 2019

Thore Oltersdorf
"Auslegung und experimentelle Untersuchung eines 3-Fluid-Wärmeübertragers für Mehrquellen-Wärmepumpensysteme" (Design and Experimental Investigation of a 3-Fluid Heat Exchanger for Multi-Source Heat Pump Systems) | Technical University of Hamburg-Harburg | 2019

Jose Eduardo Ruiz Rosero
"Precursors Evaluation for GaInNAs Growth by MOVPE Technique for Solar Cells Production" | Pontifical Catholic University of Rio de Janeiro | 2019

Shivenes Shammugam
"Raw Materials and Energy Transformation Process – Analysis of Supply Bottlenecks and Implications on Metal Markets" | University of Augsburg | 2019

Peter Schöttl
"Optical and Thermo-Hydraulic Simulation and Optimization of Solar Tower Receivers" | Technical University of Munich | 2019

Annette Steingrube
"Sozio-ökonomische Modellierung des Ausbaus erneuerbarer Energien in Privathaushalten am Beispiel Photovoltaik und Heizungssysteme" (Socio-Economic Modelling of the Expansion of Renewable Energy in Private Households as Illustrated by Photovoltaics and Heating Systems) | University of Freiburg | 2019

Philip Sterchele
"Analysis of Technology Options to Balance Power Generation from Variable Renewable Energy" | University of Freiburg | 2019

Jessica Thomsen
"Modeling and Evaluation of Regional Electricity Systems with High Shares of Renewable Energy and Flexibility Technologies" | University of Duisburg-Essen | 2018

Andreas Velte
"Experimentelle Arbeiten und Entwicklung von numerischen Modellen zur Analyse und Optimierung von erweiterten Adsorptionskreisläufen für die Wärmeversorgung von Gebäuden" (Experimental Work and Development of Numerical Models to Analyze and Optimize Extended Adsorption Circuits for Building Heating Supply) | University of Freiburg | 2019

Kübra Yasaroglu Unal
"Preparation of a TiO_2 Porous Layer by Molding of Polymer Beads for Perovskite Solar Cell Applications" | University of Freiburg | University of Strasbourg | 2019

Professorships

Dr. Andreas Bett
Appointment to the chair of "Solare Energie – Materialien und Technologien" ("Solar Energy – Materials and Technologies") in the Faculty of Mathematics and Physics at the University of Freiburg | 2020

Dr. Christopher Hebling
Honorary professorship in Chemical Engineering in the Faculty for Engineering and Construction | University of Cape Town (UCT) | South Africa

Dr. Elke Lorenz
Post-doctoral lecture qualification "Solar Irradiance Forecasting for System Integration of Solar Energy" | Carl von Ossietzky Universität Oldenburg | 2019

1 *Honoring doctoral students at the Fraunhofer ISE annual meeting for 2019: from left to right: Prof. Hans-Martin Henning, Hannes Fugmann, Annette Steingrube, Markus Niemeyer, Gregor Bern, Andreas Velte, Peter Schöttl, Harry Kummer, Sebastian Johannes Ernst (2018), Sebastian Nold (2018), Thore Oltersdorf, Mathias List, Thorsten Müller-Eping, Prof. Andreas Bett.*

POSSIBLE ENERGY SCENARIOS IN GERMANY

Following the study on the German energy transformation that was published in 2015 and was based on the REMod simulation model of Fraunhofer ISE, a new edition has appeared which illustrates different scenarios for cost-optimized transition routes for the German energy system. In contrast to the first study, reference is now made to "consistent energy scenarios". What is meant by this concept?

Henning: Whereas we had chosen a purely technical-economic approach in the previous study to demonstrate cost-optimized routes for the energy transformation, our current study now takes into account that the energy transformation is indeed a project that affects all of society. Consequently, we effectively present narratives about different energy scenarios in this study. For example, the energy transformation could develop in a way that most of the population is not willing to change well-established behavior patterns to any significant extent and that associated incentives are not really effective. For example, this would mean that not many gas-fuelled boilers would be replaced by heat pumps or that a large proportion of the population behaves conservatively with regard to mobility and does not change rapidly or comprehensively. In the study, we describe what effect this has on the development of infrastructure, on the import of energy derived from renewable sources and on costs, based on the still valid assumption that the German climate targets will be reached. Another energy scenario considered by us is characterized by "sufficiency", which means that people cut down on consumption to a certain extent or there is at least no further growth in living area and the number of vehicles, and efficient energy usage plays an important role. Another scenario is one in which changes to infrastructure continue to encounter major resistance, which applies particularly to the expansion of wind energy and electricity grids. For all of these scenarios, we then also consider the implications in comparison to a development which is cost-optimized but does not take account of any such boundary conditions within society.

In comparison to the first study, the new scenarios set 95 % CO_2 reduction as a minimum goal, and the degree of electrification for the German energy system and particularly the expansion of photovoltaics have also been adjusted upwards. Why?

Bett: In principle, we had already suspected five years ago that the assumption of reducing CO_2 emissions by 80 % by 2050 with respect to the 1990 level would not be sufficient. However, more recent calculations by the IPCC clearly show that this is not enough and at least 95 % must be the target. Concerning demand, we have to recognize that, despite growing energy efficiency, we will require more electricity, about twice as much as today in 2050, in other words, about 1000 to 1200 TWh. In our original model, we assumed equal capacity expansion for wind and solar energy. In the current study, we address the question of whether and with which consequences a more limited expansion in wind power can be compensated by PV, and draw the conclusion that this is indeed possible. In this case, PV would be extended to more than 500 GW.

How then can 500 GW photovoltaics be installed in Germany?

Bett: This amount of photovoltaics does not have to be mounted only on roofs or open land areas, which could also raise questions of acceptance. However, there are many different ways of integrating PV into our built environment and thus make double use of areas that are already occupied. At Fraunhofer ISE, we have started a major activity on Integrated Photovoltaics: For example, we develop modules for building integration, for vehicle roofs, PV power stations on water-covered areas and agrophotovoltaics (pages 18–19). And of course, when accelerated PV expansion is planned, we also have to take the consequences for systems integration into account. Among other aspects, the orientation of the PV modules, more flexible utilization options and storage, of course, all play a role.

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Why do you concentrate particularly on 2030 and 2050 in the transformation calculations?

Henning: The more imminent the targets, the more urgent and essential they become for immediate implementation. Since it has become clear that, in all probability, the German reduction target of 40 % for 2020 will not be reached, the next decadal target for 2030 is of vital importance for politics. The intermediate target for 2030 is also highly relevant because decisions must be made already today which strongly depend on whether an 80 % or a 95 % reduction in emissions is to be pursued for 2050.

Which role does hydrogen play for mobility and other sectors?

Bett: I think that we will need both purely battery-equipped vehicles and fuel cell-powered electric vehicles for sustainable mobility. At this point, I refer to a study analyzing the life cycles of both forms of mobility. For heavy freight transport, there is the option to produce synthetic fuels on the basis of hydrogen and supply power also for this transport sector, meaning aviation, ships and heavy road transport. Hydrogen adopts a key position in the entire system as an intermediary between different sectors. It serves as a storage medium for electricity, but can also be used for heating and transport. One highly relevant application field for hydrogen is also its usage in industry, primarily the chemical and steel industries. The German Federal Government recently started to develop a hydrogen strategy. In this context, Fraunhofer ISE collaborated with Fraunhofer ISI and further Institutes to publish a Fraunhofer hydrogen road map. The versatility of hydrogen, and the fact that it could actually be produced most cost-effectively in regions that are rich in solar energy and wind power, then led us to the dimension of changing our global energy supply, even when our initial main concern was the German energy transformation.

The building sector is still responsible for a significant share of CO_2 emissions. Which routes lead to an emission-free supply of heat and cooling energy?

Henning: For the building sector, fundamentally two central approaches are available: Reducing the energy demand particularly for space heating by energy retrofit of buildings and providing the remaining required energy from renewable sources. Heat pumps play an important role in this route, but also heating networks prove to be viable in the calculations. They could become an enabler for urban energy management, providing a reservoir where heat could be fed in from a wide variety of sources, from large-scale heat pumps, through large combined heat and power plants, up to output from solar collectors and waste heat from industry. Of course, many further-reaching options for using solar energy become possible when building envelopes become "solarized" to a major extent.

When will we experience a completely fossil-free energy scenario in Germany?

Bett: Technically, we could certainly achieve climate neutrality by 2035; Fraunhofer ISE provides developments across the whole spectrum to support this. However, I do not believe that this is realistic on socio-political grounds. For that reason: 2050 at the earliest.

Henning: Achieving a climate-neutral energy supply by 2050 is ambitious. However, it is essential that we strive for this goal – particularly as the urgency appears to be increasing, with recent statements from climatologists indicating that the previous predictions on the effect of emissions tended to be too conservative.

1 *Director of the Institute, Prof. Hans-Martin Henning.*

2 *Director of the Institute, Prof. Andreas Bett.*

INTEGRATED PHOTOVOLTAICS – USING SURFACE AREAS TWICE

To achieve the energy transformation with up to 100 % prevention of CO_2 emission in all sectors, the installed photovoltaic system power in Germany must be increased by a factor of ten to about 500 GW. This is feasible if the expanded PV capacity is not restricted to roofs and open areas but is also integrated into the existing built environment. In 2019, Fraunhofer ISE thus defined a strategic focus on Integrated Photovoltaics within its Photovoltaics business area, and thereby brought together several activities and areas of competence that had already become established. Integrated photovoltaics offers diverse applications and opens up an enormous potential surface area for generating photovoltaic electricity, from building-integrated PV, through vehicle exteriors or floating PV on water surfaces, to PV along transport routes and agrophotovoltaics, which allows double land usage by mounting PV modules higher up above the ground – harvesting crops and electricity from the same land area. Building-integrated photovoltaics and agrophotovoltaics alone each have a technical power potential exceeding 1 terawatt in Germany. Integrated PV even creates synergetic effects in many cases, increasing mileage for electric vehicles or providing noise protection along roads and railways. Generating solar power close to the consumer or directly aboard vehicles also reduces the load on the power grid.

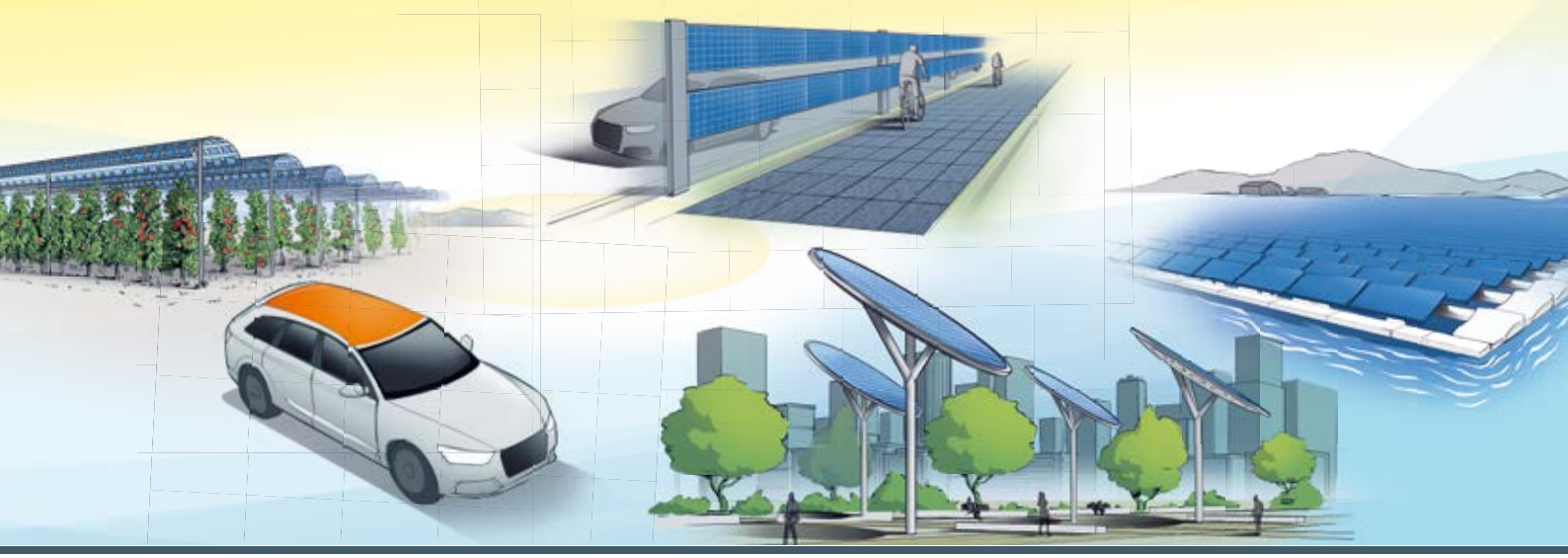
Fraunhofer ISE has developed technologies for the integration of PV modules which allow free selection of module formats and colors and can also meet specific requirements such as reduced weight per area, appealing aesthetics or resistance to extreme mechanical loads. Fraunhofer ISE develops solutions to meet the needs of diverse applications and clients.

Building-Integrated PV (BIPV)

In building-integrated photovoltaics, construction elements not only generate power but also provide thermal insulation and protection from wind, noise and weather while adding new design options. As a result, BIPV makes a significant contribution to reducing building-related CO_2 emissions. Fraunhofer ISE has developed flexible formats, high-efficiency solar cells with filigree metallization and color variations which offer aesthetic options for solar modules integrated into building façades or roofs. One example is given by colored MorphoColor® modules: thanks to their special coating on the glass cover, these modules can be manufactured in any spectral color with high color saturation and angular stability, while the relative efficiencies are lowered by only seven percent.

Agrophotovoltaics (APV)

Agrophotovoltaics involves the installation of solar modules over arable land, enabling an expansion of PV power output while simultaneously using the land for agricultural purposes. As part of a research project in Germany near Lake Constance, Fraunhofer ISE was able to demonstrate a 60–84 % increase in land-use efficiency as well as improved agricultural resilience during dry periods. Additional benefits include protection against damage caused by hail, drought and frost, a reduced need for irrigation and the option to use solar power directly on site.



Vehicle-Integrated Photovoltaics (VIPV)

In vehicle-integrated photovoltaics, solar modules replace parts of the vehicle exterior and supply power to electrical components or feed energy into the drive batteries of electric vehicles, thereby increasing the distance they can drive on a single charge. Aesthetic standards and module efficiency are especially important factors when integrating solar modules into vehicles. Fraunhofer ISE has developed a spherically curved solar car roof with high-efficiency solar cells that boast an output of about 210 W/m^2. Overlapping connections in a shingle system allow optimal use of the module area for generating power while maintaining a homogeneous and attractive overall appearance. Lower resistance losses and the elimination of shading via cell connectors in conjunction with a particularly high shading tolerance improve absolute module efficiency by as much as two percent compared to conventional solar modules. Fraunhofer ISE is also exploring glass-free structures for lightweight applications in commercial vehicles.

Road-Integrated PV (RIPV)

Road-integrated photovoltaics involves embedding solar modules in, on and above transportation routes. Applications range from direct integration into streets, footpaths and public squares to use in railways and other traffic-related surfaces such as noise protection walls and shoulder lanes. Given that roughly 5 % of Germany's total surface area is covered by transportation routes, making use of already sealed horizontal surfaces opens up enormous technological potential.

Solar modules that are integrated directly into roads must offer a sufficient degree of traction for all road users, regardless of the weather conditions, requiring the development of durable, structured module surfaces.

Floating PV (FPV)

Floating PV systems, with modules mounted on buoyant bodies that float on standing water or the ocean's surface, have experienced dynamic growth worldwide (over 1.1 GW of installed capacity as of mid-2018). Germany also has a huge potential to capitalize on this technology in pit lakes, flooded gravel pits and, in some cases, reservoirs. The advantages offered by FPV lie in its inexpensive large-scale implementation, the increase in PV efficiency thanks to the water's cooling effect and lower rates of evaporation, which help to limit water loss.

Urban Photovoltaics (UPV)

Urban photovoltaics uses sealed areas in cities, towns and villages to generate electricity from renewable sources and to create attractive urban landscapes. Examples include large parking lots, public squares or sport and recreation areas, where photovoltaics is installed to provide shade or in combination with lighting, charging infrastructure for electromobility or rain shelters. This adds value to the spaces for users and allows them to experience the energy transformation positively. Further examples include the combination of photovoltaics with lighting, shading and rain protection in central bus stations or over the parking areas of large exhibition or sports grounds.

PHOTOVOLTAICS

Photo: Pre-manufacturing research for solar cell production is carried out by Fraunhofer ISE in the PV-TEC – Photovoltaic Technology Evaluation Center, which was comprehensively modernized in 2018.

Photovoltaics is perceived to be a game changer for the global energy system by the Global Alliance of Solar Energy Research Institutes (GA-SERI), of which Fraunhofer ISE is a member together with NREL (USA) and AIST (Japan). An article to this effect was published in the journal "Science" in May 2019. Dramatic cost reduction and the rapid expansion of production capacity have led to this perception. Not only the electricity sector but also transport, heat, industry and chemical processing will be powered to a large extent by electricity in future. This scenario offers opportunities but also raises challenges – both at the level of the energy system and also with regard to research and industry. At the end of 2018, PV power amounting to about 488 GW was installed. 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 effects. In Germany, competitive levellized costs of electricity of 4 to 5 euro cents per kWh can be achieved today. In order to successfully realize the energy transformation and approach the goal of a CO_2-free energy supply, we need to expand photovoltaic installation to an extent that can no longer be accommodated on roofs or open land areas. We have thus initiated work on the topic of "Integrated Photovoltaics" at Fraunhofer ISE (pages 18–19).

Research and development have made essential contributions to this success story. Fraunhofer ISE contributes to continuous improvement in efficiency and use of mate-

rial 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 efficiencies. We are transferring wafer processing from its previous location in Freiberg to the Center for Silicon Photovoltaics (CSP) located in Halle. A further major topic there is recycling, which is becoming increasingly important. Preparatory research for industrial implementation is carried out by Fraunhofer ISE in our PV-TEC – Photovoltaic Technology Evaluation Center.

A promising approach to overcome the Auger limit of 29.4 % for the efficiency of single-junction silicon solar cells is presented by tandem solar cells. In developing tandem concepts, we benefit from competence gained over more than four decades in silicon solar cells and in the production of multi-junction solar cells. In 2019, we were able to improve the world record for a monolithically produced, multi-junction solar cell of III-V semiconductors and silicon to an efficiency value of 34.1 %. We achieved a value of 24.5 % for a tandem cell consisting of perovskite on silicon. In concentrator technology, we demonstrated top efficiencies for multi-junction cells of up to 46.1 % and a record module efficiency of 41.4 %. Our work on organic and perovskite solar cells opens up interesting perspectives and application areas.

In addition, Fraunhofer ISE further develops successful procedures for the accurate characterization and yield analysis of cells and modules. Our accredited calibration laboratory, CalLab PV Modules, achieves an internationally leading measurement uncertainty of only 1.1 %. 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, manufacturing procedures, use of materials and a sustainable processing chain.

SILICON PHOTOVOLTAICS

344
Total staff

54
Journal articles and contributions to books

86
Lectures and conference papers

9
Newly granted patents

Our newsletter offers regular updates on our research milestones!

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, efficiencies play a decisive role for further reducing the levellized 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 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 efficiencies 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. As a new beacon for our solar cell research, we will be opening the new building for our Center for High Efficiency Solar Cells in 2020.

Selected Milestones in 2019

- Presentation of area-saving shingle solar cells with high efficiencies
- Efficiency records for monolithic triple-junction solar cells based on silicon
- Presentation of a study on setting up PV production in Germany
- Reduced silver consumption due to novel fine-line screen-printed metallization

Photo: View into screen-printing equipment.

www.ise.fraunhofer.de/silicon-photovoltaics

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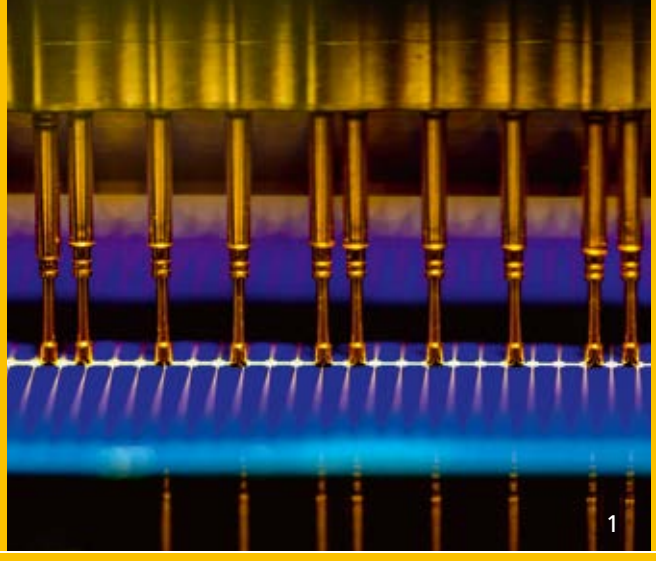
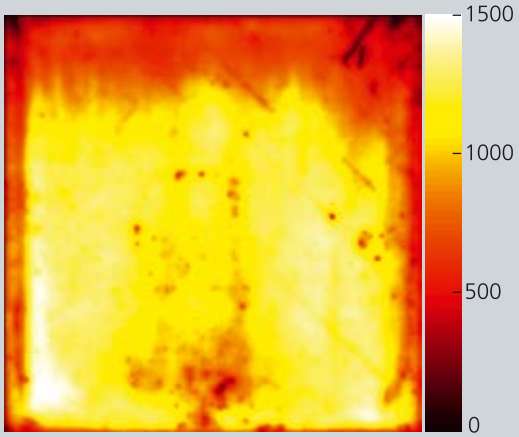
Selected Projects in 2019

- CUT-A PLUS – Cutting-Edge Characterization and Technology for Germany's PV Industry
- PV-BAT400 – PV-BAsis Technology for Highly Efficient Modules with 400 W Power and Power Density of 240 W / m^2
- DISC – Double Side Cells with Innovative Carrier-Selective Contacts
- EmitterPlus – Integrated Process for Formation of Gas-Phase Emitters and Selective Contacts

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





2

Inline Test of Solar Cells: Extremely Flexible Measurement Platform

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The higher efficiency of novel solar cells is accompanied by a greater sensitivity to material and processing fluctuations. To improve the control of these variations better and identify further potential for process improvement, relevant inline characterization procedures are crucial.

To develop and evaluate these procedures, Fraunhofer ISE operates an extremely flexible inline solar cell tester for very diverse cell concepts in its PV-TEC – Photovoltaic Technology Evaluation Center. Its core is a measurement facility, in which the electrical performance data also of bifacial solar cells can be measured in fractions of a second under illumination only from the front, only from the back and from both directions by two independent xenon flash tubes. This allows the development and application of new sorting algorithms for optimized bifacial yields and internally homogeneous modules under different illumination scenarios. Automated characterization of solar cells without bus bars, back-contact solar cells and solar cells in whole-cell, half-cell and shingle formats is also possible. The measurement system can correct any hysteresis effects that may occur. In addition to the measurements of electrical performance, measurement systems for electroluminescence and photoluminescence imaging, thermography, spectrophotometry and spectral sensitivity are integrated, which allow the comprehensive analysis of losses and potentials. Furthermore, we can temporarily add further systems and components into the automated set-up for evaluation purposes.

High-Quality Cast Monocrystalline Silicon with SMART Seeding Technology

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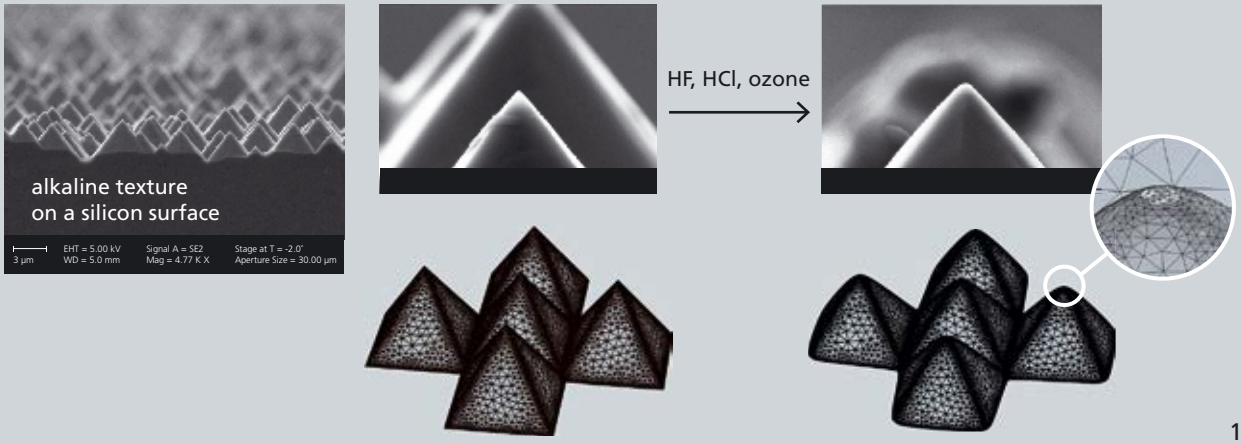
High-efficiency solar cells with PERC or TOPCon structures require high-quality silicon wafers as the raw material. Fraunhofer ISE is working on new processes for resource-saving production of monocrystalline wafers, applying the cast monocrystalline process as an alternative to the established Czochralski process to grow monocrystalline ingots. Special configurations of monocrystalline seeding plates on the bottom of a solidification crucible are used to grow a predominantly monocrystalline block from the molten phase according to the principle of directional solidification.

By combining large seeding plates with thin strips of silicon according to the concept of "Seed Manipulation for ARtificially controlled defect Technique" (SMART), we have produced material with deliberately introduced functional defects, which features significantly fewer undesired crystal structural defects and thus higher material quality throughout the whole wafer. In industrially relevant solar cell processes, the produced wafers display a comparable efficiency potential to Cz silicon. For example, PERC solar cells with an efficiency of 21.4 % were made of p-type wafers and TOPCon solar cells with an efficiency of 23.3 % were produced from n-type wafers. Further work is focussing on transferring this technique successfully from the laboratory to a modern industrial scale and further reducing costs and CO_2 emissions for this production step.

1 *Electric contacting of solar cells during power measurements with spring-balanced probes.*

2 *Charge carrier lifetime (in µs) of a 10 × 10 cm² SMART mono-Si wafer after high-temperature processing.*



1

Digital Twins in the Production of Solar Cells

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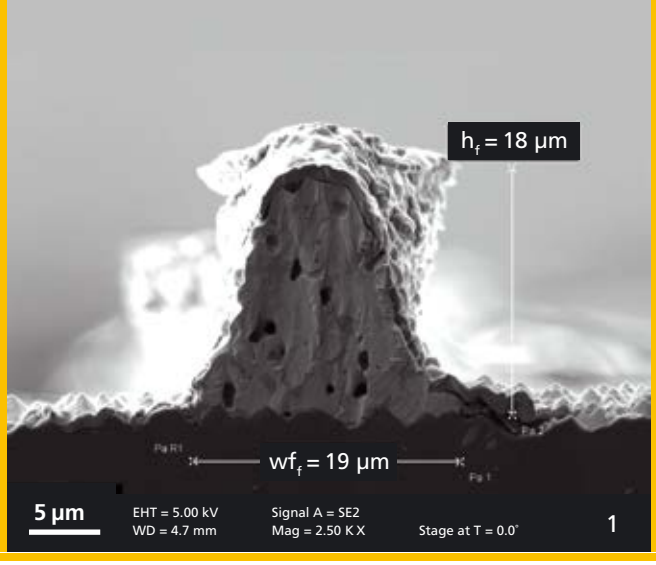
Comprehensive digitalization of production and business processes is considered to be the next major technological revolution, which promises to bring great savings along the entire value chain in future. In order to exploit the potential of digitalization, digital models of both the produced items and the production equipment must exist that are as complete and realistic as possible. These are called digital twins.

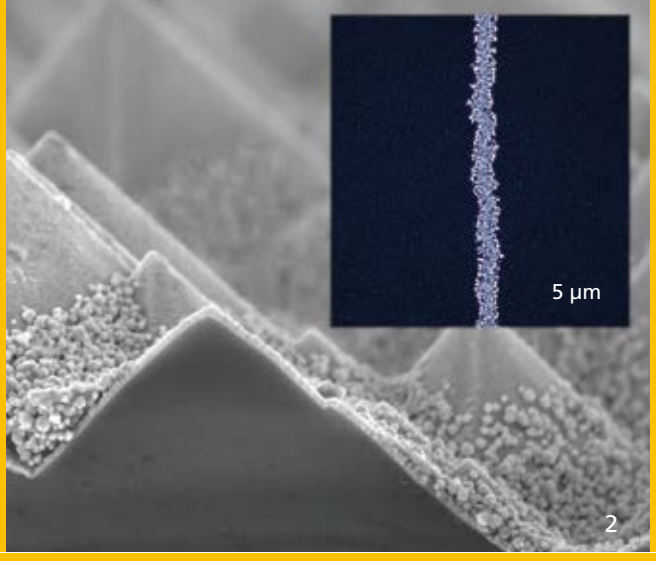
The digital twin of processing equipment initially contains static information about the configuration of the system, but beyond this, also all values from sensors and actuators are available in real time. These sensor values can be used to analyze the state of the equipment. In particular, this allows for the early detection and even prediction and prevention of faults in the system, before they actually occur. To this purpose, a concept to diagnose existing errors and predict future faults was developed at Fraunhofer ISE. It is based on an inference machine which analyzes the incoming sensor values on the basis of complex algorithms. Extensive knowledge from systems and process engineers can be stored there.

In addition to the equipment, the process itself is also a subject of great interest. A sufficiently accurate model of a process can already predict its result if the digital twin of the input material is taken into account. These models can be established at different levels of abstraction. Ab initio models apply the underlying physical relationships and are capable of predicting the processing result with great precision. Calibration and training data sets are not needed for this approach. At present, finite-element calculations are used to characterize microscopic etching processes for the surfaces of solar cells.

However, these models often require large computing power resources and cannot be applied in real time with the computers that are currently available. For this reason, the exact models are often approximated by meta-models. For rapid prediction of processing results, we at Fraunhofer ISE have successfully applied deep learning methods for automated image processing. To this purpose, a specially adapted convolutional neuronal network (CNN) has been trained with a large amount of data. Photoluminescence images of multi-crystalline wafers were used as the input data. The model now contains all of the necessary information about the entire cell process and is capable of providing a prognosis for the electrical characteristics of the cell to be produced on the basis of a photoluminescence image.

1 *Simulation model of the surface covered with a pyramidal texture. Left: before the cleaning process, right: after the cleaning process. Upper row: SEC images from experiments, lower row: corresponding digital twins.*





Fine-Line Metallization Reduces Silver Consumption

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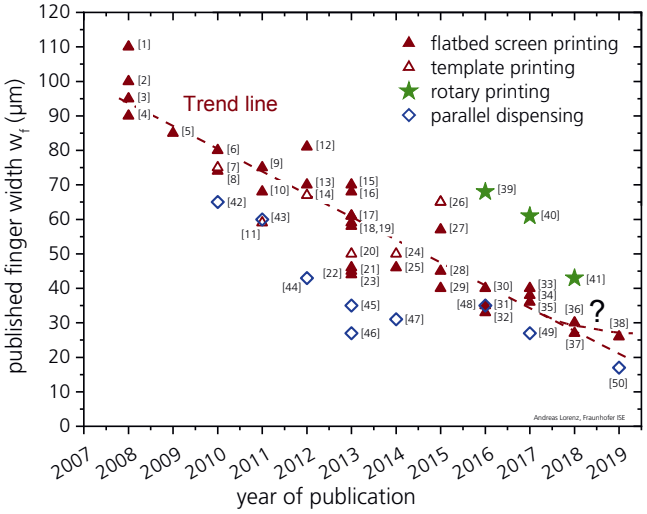
The key challenge concerning the metallization of silicon solar cells is to reduce the consumption of silver, an expensive resource, and simultaneously increase the efficiency. In process development, we are thus working on implementing contact fingers that are as narrow as possible and sufficiently high for current transparent, as well as evaluating alternative materials. Different metallization processes are developed and optimized at Fraunhofer ISE to meet these requirements.

Classic flatbed screen printing with fine-meshed screens and the multi-nozzle dispensing technology, which was developed at Fraunhofer ISE and is now due to be commercialized by a spin-off, enable the production of contact fingers with widths and heights in the 15–20 µm range in a single printing step. The silver consumption can be reduced in this way by up to 30 % compared to the current industrial standard with contact finger widths of 30–35 µm. Addressing rotary printing technology, we are currently carrying out research to increase the system throughput by a factor of two.

With the "FlexTrail" process that was recently developed at Fraunhofer ISE, contact widths of around 10 µm can be achieved. The contact height of only a few µm makes integration into novel module concepts with wire circuits feasible, in which conventional bus bars are no longer needed and ten or more wires are used instead. This allows the silver consumption to be reduced by at least a factor of ten.

An alternative approach is the production of very narrow contacts with laser transfer processes. After galvanization with nickel and copper, the contact widths are around 20 µm. The advantage of this approach is that a large number of different metals can be used and silver can be replaced completely.

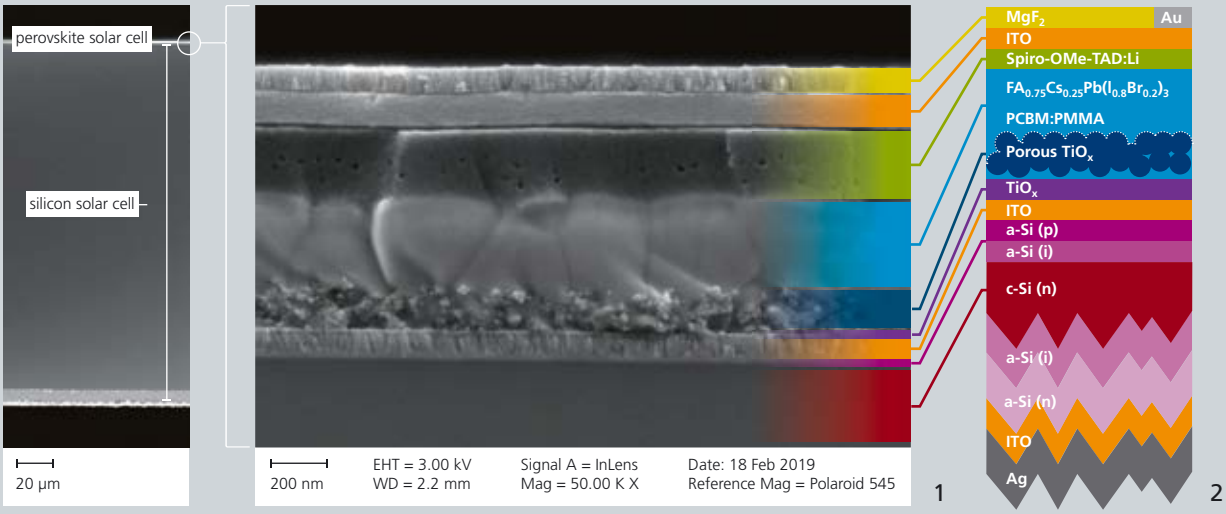
Efficiencies exceeding 22 % of large-area silicon solar cells demonstrate the high efficiency potential for the metallization processes that have been presented here. Future research work is aiming to increase the efficiency still further, reduce the silver consumption and increase the productivity of the production lines. In future, the competence gained in fine-line metallization should also be applied increasingly in other business areas of Fraunhofer ISE, e.g. in production technology for fuel cells.



Graph: Development of the printed contact finger width over the past ten years for different printing processes.

1 *Scanning electron micrograph of the cross-section of a fine-line contact finger that was produced by screen printing.*

2 *Scanning electron micrograph and microscope image of a fine-line contact finger that was produced by the "FlexTrail" process.*



In Tandem toward Highest Efficiencies at Low Cost

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The efficiencies of silicon solar cells are fundamentally limited to 29.4 %. This is a limit which is rapidly being approached, with efficiencies exceeding 26 % on a laboratory scale and an increase in the efficiencies from industrial production of 0.5 % per year. By contrast, silicon-based tandem solar cells make efficiencies exceeding 30 % feasible. Here, a second solar cell made of a semiconductor with a larger band gap efficiently converts the photons with high energy. The photons with low energy are converted by the silicon solar cell.

The combination of perovskites with silicon is particularly promising. Perovskite solar cells achieve high efficiencies and can be produced cost-effectively. In detailed cost calculations, we demonstrated that the application of perovskite-silicon tandem solar cells is particularly attractive for roof-mounted systems. Here, the available areas are limited and the installation costs tend to be higher. The benefit of high efficiency is thus particularly high.

With high-efficiency hetero-junction silicon solar cells, the development of a stable perovskite absorber with a bandgap of 1.7 eV and the application of novel surface passivation layers in the perovskite solar cell, we produced perovskite-silicon tandem solar cells with a record open-circuit voltage exceeding 1.8 V. A decisive contribution was made by developing a particularly gentle sputtering process to deposit indium tin oxide (ITO) as the conductive contact layer on the front surface.

To prepare the industrial production of perovskite-silicon tandem solar cells, we are investigating different types of deposition technology for the perovskite absorbers that are suitable for upscaling. These include evaporation and spray-coating and their combination in hybrid processes, as well as processing technology to deposit contact layers such as sputtering of NiO_x and atomic layer deposition of SnOx. In addition, we are studying the application of TOPCon technology for the silicon solar cell and the connection of the perovskite and silicon solar cells via a silicon-based tunnel diode.

Due to the higher efficiency of perovskite-silicon tandem solar cells, the consumption of resources also decreases in comparison to purely silicon-based photovoltaic systems. In order to improve the ecological balance further, we – together with five other Fraunhofer Institutes – are developing new materials and solar cell structures within the Fraunhofer-funded "MaNiTU" project, which is investigating materials for sustainable tandem solar cells with the highest conversion efficiency. Here, the focus is on replacing the lead which is still present in small amounts in the absorber and increasing the efficiency.

1 *Electron micrograph of a perovskite-silicon tandem solar cell. The perovskite solar cell consists of only a very thin layer on top of the silicon solar cell.*

2 *Structure of the perovskite-silicon solar cell. Surface passivation and optimized contact and absorber layers allow record voltages to be achieved.*

III-V AND CONCENTRATOR PHOTOVOLTAICS

46
Total staff

14
Journal articles and contributions to books

20
Lectures and conference papers

2
Newly granted patents

Our newsletter offers regular updates on our research milestones!

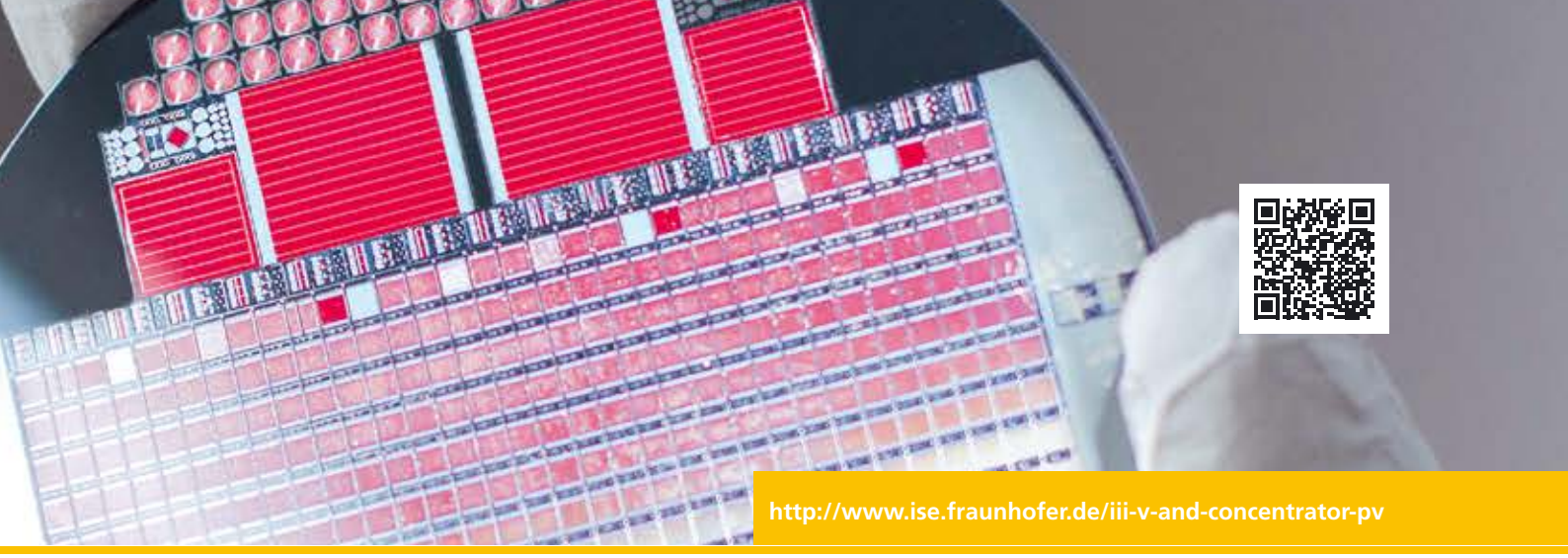
Within this topic, Fraunhofer ISE addresses the demands of space and concentrator photovoltaics. In addition, we work on efficient conversion of light from other sources like lasers into electricity. We investigate both solar cells of the next generation with optimized structures and efficiencies and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

In concentrator 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, packaging and technology, as well as theoretical modelling and module design. We thus serve a heterogeneous market of enterprises which develop PV systems with low to very high concentration factors. For the latter, our expertise also extends to system aspects such as application of the generated heat, desalination of seawater or direct production of solar hydrogen. We achieve innovations by systems-relevant conception and set ourselves the goal of providing the best solutions 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 2019

- Wafer-bonded III-V//Si tandem cell for the first time with an efficiency of 34.1 % (AM1.5g)
- GaInP / AlGaAs / Si triple-junction solar cell grown directly on silicon with an efficiency of 24.3 % (AM1.5g)
- New four-junction of GaInP/GaAs /GaInAs //GaSb with an efficiency of 43.8 % at a concentration of 796 suns
- EyeCon hybrid concentrator module with an area of 1088 cm^2 generates 326 W / m^2 in Freiburg
- New CPV micro-module with reflective optics achieves a module efficiency of 29.7 % with a high acceptance angle of 0.6 ° and a module depth < 25 mm
- HIPERION project (HybrId Photovoltaics for Efficiency Record using Integrated Optical techNology) receives a subsidy of 10.6 million euros to develop the industrial production of high-efficiency solar modules on a large scale

Photo: Wafer with highly efficient III-V concentrator solar cells, which radiate red light when illuminated by the camera flashlight – a sign of high material quality.



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

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Selected Projects in 2019

- PoTaSi – Demonstration of the Potential of Monolithic Tandem Solar Cells of III-V Semiconductors and Silicon
- HeKMod4 – Highly Efficient Concentrator Module with GaSb-Based Four-Junction Solar Cell
- CPVMod – CPV Module with a Modular Design
- KoReMo – Cost Reduction and Resource Efficiency by New Supply Systems for Metal-Organic Precursors for Epitaxy of III-V High-Power Solar Cells
- ALFAMA – Advanced Lightweight and Flexible Array with Mechanical Architecture
- RadHard – Ultra High Efficiency Radiation Hard Space Solar Cells on Large Area Substrates

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

Rapid Growth of III-V Semiconductor Layers for Solar Cells

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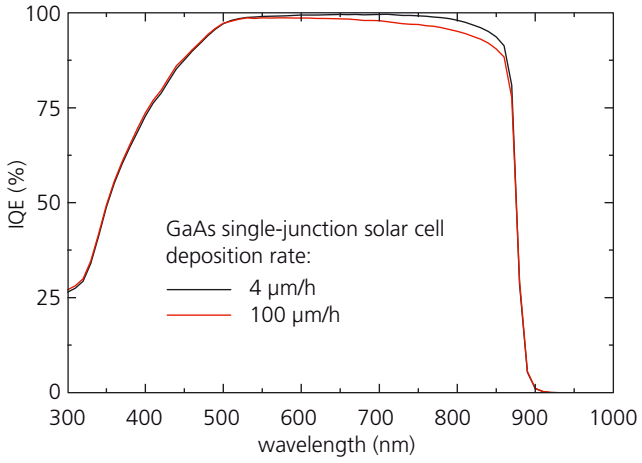
Multi-junction solar cells of III-V compound semiconductors are the most efficient by far in converting sunlight to electricity. Nevertheless, their application is limited to niches such as power supplies for satellites. This is particularly due to their material and production costs, which are around one hundred times higher than those for silicon solar cells. We are thus working on solutions to make the processes less expensive in future. One approach is to use inexpensive substrates. For example, we recently produced a GaInP/GaAs//Si triple-junction solar cell for the first time, with an efficiency of 34 %. Another important approach is to reduce the cost of epitaxy to deposit the III-V semiconductor layers. Modern processes from optoelectronics and microelectronics are designed for high precision and small production volumes. By contrast, very large areas are needed in photovoltaics, but some of the specifications on the thin films can be relaxed. In the "MehrSi" project, which is funded by the German Federal Ministry for Education and Research (BMBF), we have investigated how much the deposition rate and deposition efficiency can be increased for GaAs layers. Last year, we achieved a growth rate of 280 µm / h for the first time applying metal-organic vapor phase epitaxy (MOVPE), the standard method for producing III-V solar cells industrially. This rate is thirty times higher than the previous typical growth rate. Simultaneously, the efficiency of Ga incorporation was increased by about 60 % and the consumption of group V materials was reduced by a factor of 6. At a rate of 100 µm / h, the absorber layer of a GaAs solar cell was deposited in 2 minutes and an efficiency of 23.3 % was measured in comparison to 24.6 % for a reference structure grown at 4 µm / h.

The growth rate for the $Ga_{0.5}In_{0.5}P$ top cell was mainly limited by the indium precursor to date. Typically, trimethylindium was used, which is a solid with a low vapor pressure that limited the amount of indium which could be fed into the process. To overcome this, a novel liquid trimethylindium source with a direct evaporation system was integrated into an existing production system within the "KoReMo" project. Compared to a solid source, 20 times more indium can be fed into the reactor using this approach. An initial GaInP solar cell that was prepared with this new process has already achieved comparable solar cell parameters to a conventionally produced reference.



Graph: Internal quantum efficiency as a function of wavelength of a GaAs solar cell deposited at 100 µm/h (red) in comparison to a reference grown at the standard low growth rate of 4 µm/h (black).

1 *View into the reactor chamber of a closed coupled showerhead MOVPE reactor used for growing GaAs at growth rates up to 280 µm/h.*

Evaluating Concentrator PV Technology in India

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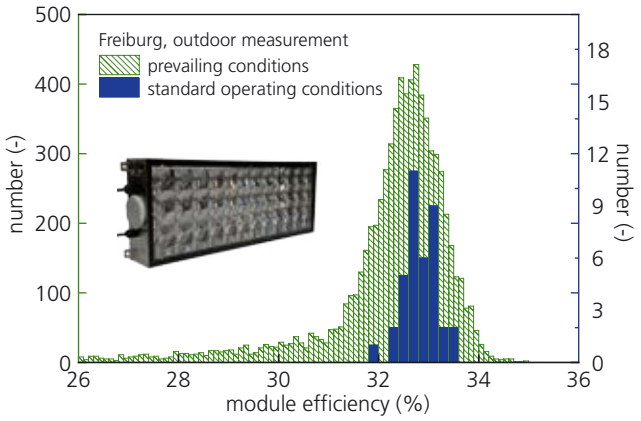
In concentrator photovoltaics (CPV), sunlight in regions with a high proportion of direct solar irradiance is concentrated by lenses onto small, highly efficient, multi-junction solar cells. In this way, CPV modules achieve efficiencies that clearly exceed 30 %. At present, there is no other PV technology with similarly high conversion efficiency. However, the modules must track the sun accurately. Together with NETRA, the research facility of the largest Indian energy utility NTPC, we are investigating the specific requirements and challenges encountered when applying CPV systems in India. The German-Indian project is supported by the German Kreditanstalt für Wiederaufbau KfW with funding from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Fraunhofer ISE has been measuring CPV modules for more than 20 years. We have developed measurement procedures with which we can determine the rated electric power of the modules under concentrator standard test conditions analogous to the IEC 62670-3 standard. For this purpose, several thousand single measurements are evaluated (see graph). In addition, we support the provision of data sets to calculate the annual energy yield, e.g. with the "PVSyst" program.

The focus of our work in India is on evaluating CPV systems and modules, as well as knowledge transfer. We have conducted seminars locally, to promote the understanding of CPV technology in this country with its growing demand for electricity generated from renewable sources. Furthermore, an outdoor test rig with a tracker and measurement electronics was constructed on the grounds of our research partner, NETRA, in Greater Noida. Here, CPV cells and modules can be investigated under the irradiance and meteorological conditions in India, with high temperatures and a high aerosol content in the atmosphere. At the same time, meteorological environmental conditions such as solar irradiance, solar spectrum and air temperature are continually recorded. We measure selected CPV modules and classic silicon flat modules, so that the annual energy yield of the two types of technology can be compared directly. In addition to the outdoor test rig, four commercial CPV systems made by the European companies BSQ Solar (Spain) and AZUR SPACE Solar Power (Germany) with a power of 26 kW were installed. The systems serve as references to determine realistic values for the annual energy yield.



Graph: FLATCON® CPV module produced by Fraunhofer ISE, with an efficiency of 35 % under standard test conditions (25 °C cell temperature and 1000 W/m²) and 33 % under standard operating conditions.

1 *Power station consisting of four CPV systems with a total electric power rating of 26 kW. This power station was installed in India for research purposes.*

2 *Outdoor measurement laboratory for accurate determination of the electric performance of CPV modules under standard conditions, installed in India by Fraunhofer ISE.*

EMERGING PHOTOVOLTAIC TECHNOLOGIES

37
Total staff

13
Journal articles and contributions to books

8
Lectures and conference papers

3
Newly granted patents

Our newsletter offers regular updates on our research milestones!

Emerging Photovoltaic Technology encompasses organic, dye and perovskite solar cells, photon management and multi-junction solar cells on crystalline silicon. The aim is to exploit optimization potential in photovoltaics with the help of this novel technology 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.

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. We are developing electrodes with high stability to short circuits for application in organic solar cells used as power supplies for sensors and indoor radio-controlled data loggers.

Concerning perovskite solar cells, we are working on different approaches to guarantee adequate long-term stability in addition to high efficiency. In addition to pure perovskite solar cells, we are also developing silicon-based multi-junction solar cells to make better use of the solar spectrum by reducing thermalization losses. We are also following this strategy with our work on 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.

Milestones in 2019

- Successful roll-to-roll processing of organic solar modules with a high technical yield thanks to a novel electrode system that was developed at Fraunhofer ISE
- Organic solar cell with 18 % efficiency under low-light conditions (indoor room lighting of 500 lux)
- Start of the Fraunhofer lighthouse project, "MaNiTU" – materials for sustainable tandem solar cells with highest conversion efficiency – coordinated by Fraunhofer ISE

Photo: Mask to evaporate metal contacts onto perovskite solar cells.

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

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Selected Projects in 2019

- H2OPV – Organic Photovoltaics to Cover Water Reservoirs
- ORGANAUT – Organic Photovoltaics for Autonomous Linked Sensors and Internet of Things

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

Roll-to-Roll Process for ITO-Free Organic Solar Modules

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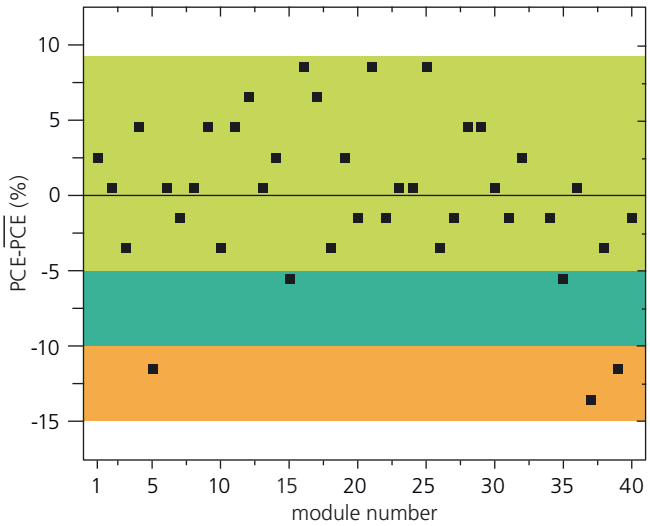
Fraunhofer ISE has successfully produced organic solar modules in an industrially relevant roll-to-roll coating process. A photovoltaic back sheet with an aluminum barrier was used as the substrate, which was coated by an industrial partner with an electrode that had been developed at Fraunhofer ISE. The electrode consists of a combination of metal and metal oxide layers, which were developed to ensure good resistance to short circuits. This is decisive, as the individual layers in organic solar cells are very thin (about 100 nm) and soft. Coating defects, which can be caused by impurities on the substrate or rollers, can otherwise lead to local short circuits. These in turn limit the efficiency of the organic solar modules or can even cause a total breakdown.

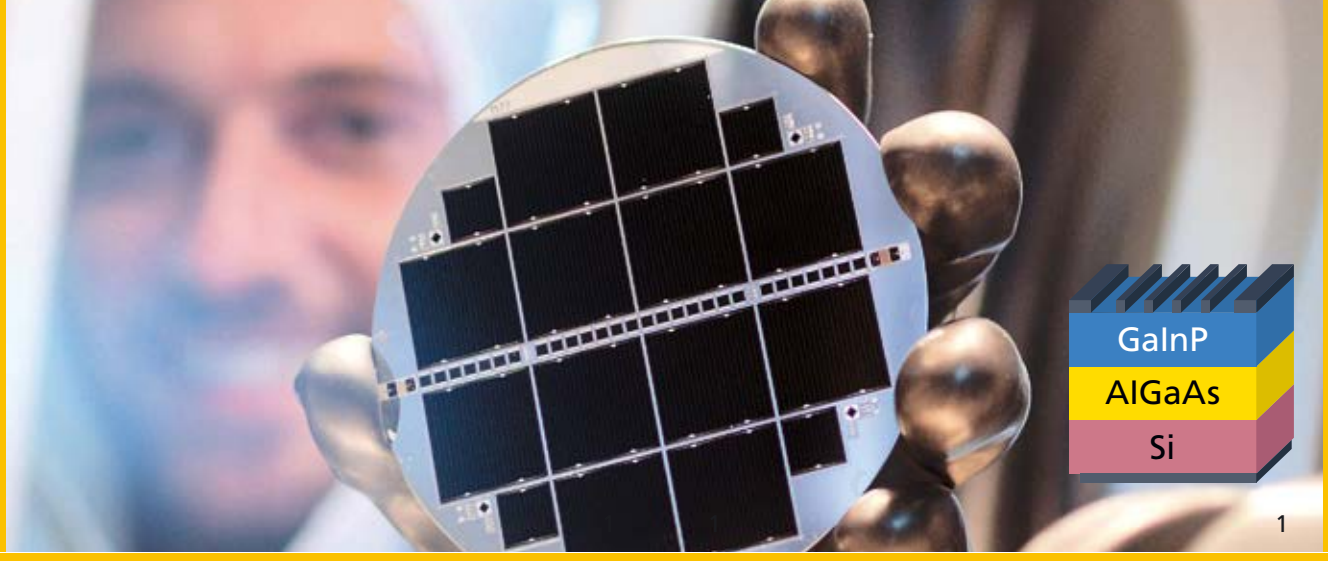
We applied the novel electrodes on flexible barrier substrates for the first time over a large area in a roll-to-roll process. The substrates were successively coated with the organic absorber and the PEDOT: PSS hole conductor, applying the slot-die coating process. A silver grid electrode was deposited as the final layer in a roll-to-roll screen-printing process. We applied a patented solvent-based structuring process to connect the individual cell strips in series. Finally, each module (with an area of 30 cm × 40 cm) was individually encapsulated with epoxy adhesive and a barrier film. In total, we measured 39 modules, without any preliminary selection.

The result illustrates the robustness of the production process. The graph shows that 87 % of the modules are better than the average minus 5 % (light green). 92 % have an efficiency that is better than the average minus 10 % (light and dark green), and only three of the 39 modules are near the average minus 15 % (orange). Correspondingly, the maximum deviation of any module efficiency from the average is 15 %. This can be clearly attributed to the applied electrodes with their high resistance to short circuits. As a result, the entire process is significantly less sensitive to coating defects. A patent claim for these novel electrodes is currently being prepared.



Graph: Deviation of the power conversion efficiency from the mean value determined from measurements of 39 modules.

1 *Roll-to-roll coated organic solar modules developed at Fraunhofer ISE. They are now being continuously measured outdoors.*



1

III-V//Si Triple Solar Cell Achieves 34 Percent Efficiency

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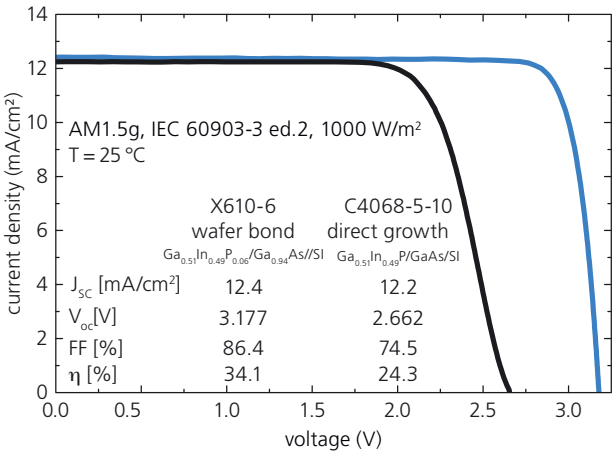
Multi-junction or tandem solar cells make it feasible to increase the efficiency for converting sunlight to electricity appreciably compared to present single-junction devices. Photons transport different amounts of energy, depending on their wavelength. Silicon, the best-known semiconductor in photovoltaics, absorbs light up to a wavelength of 1200 nm but converts all of these photons at the same voltage of about 600 mV. The fundamental principle of a III-V//Si multi-junction solar cell is to stack further absorbers on top of the silicon, consisting in this case of III-V compound semiconductors, which convert short-wavelength light at a higher voltage. Thus, the efficiency of the solar cell theoretically increases continually with the number of absorbers. In practice, we have investigated triple-junction solar cells with three sub-cells of GaInP, AlGaAs and silicon.

The complex inner layer structure of the cells is not visible from the outside. This is partly due to the high absorptance of the III-V semiconductors, which have a total thickness of only 2.5 µm. The front of the cell appears black (see photo) in order to couple in as much light as possible, and the typical metal grid of the front contact can be seen. The back surface is completely covered with evaporated metal. The difficulty in producing this type of multi-junction solar cell is to prepare the extremely thin III-V absorber with very high quality and to bond it to the silicon solar cell. One route applies direct epitaxial growth of the III-V layers onto a partly processed silicon bottom cell. Within the "MehrSi" project funded by the German Federal Ministry for Education and Research (BMBF), we achieved an efficiency of 24.3 % with this process. This is an internationally leading value for this technology, but today there are already single-junction silicon solar cells which are still better.

The challenge thus remained of improving the quality of the layers. We succeeded by applying the trick of initially growing the III-V absorber epitaxially on GaAs and then transferring it onto silicon by wafer bonding. With this type of triple-junction solar cell, we were able to demonstrate efficiencies of 34.1 % within the "PoTaSi" project that was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

The results demonstrate that multi-junction solar cells with efficiencies of 30 % and more are feasible. However, there still remains the challenge of producing the cells at economically viable costs. Achieving this goal will certainly demand several more years of research and development.



Graph: IV characteristics of two III-V//Si tandem solar cells, one grown directly on a silicon substrate and the other one bonded to a silicon sub-cell.

1 *Wafer with twelve III-V//Si tandem solar cells, each with an area of 4 cm². The cells have an internal structure with three stacked absorbers consisting of GaInP, AlGaAs and Si, which absorb different parts of the solar spectrum.*

PHOTOVOLTAIC MODULES AND POWER PLANTS

132
Total staff

9
Journal articles and contributions to books

50
Lectures and conference papers

3
Newly granted patents

Our newsletter offers regular updates on our research milestones!

Module technology transforms solar cells into durable products for safe operation in PV power plants and integrated applications. The Module-TEC – Photovoltaic Module Technology Center of Fraunhofer ISE is equipped with a wide range of modern processing and analytical platforms for connecting and laminating solar cells. We cooperate closely with our clients during materials testing and development of products and processes. Measurement and simulation are applied to analyze cell-to-module balances (CTM), and we offer licences for our "SmartCalc.CTM" calculation tool.

The reliability of modules is tested by the team in our accredited TestLab PV Modules for certification according to international standards and with reference to particular climatic loads and specific degradation risks. We analyze degradation and damage to modules that have been exposed in climatic chambers and in the field. 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 less than 1.1 % 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.

We also offer solutions to integrate photovoltaics into the building envelope, agricultural areas and areas of water. Our team develops customized, aesthetically appealing solar modules for solar-active roofs, façades, vehicle bodies, noise-protection barriers and transport routes.

Milestones in 2019

- Industrial production of solar components and their integration into building planning processes
- Completion of the "PV-Live" project with TransnetBW
- Agrophotovoltaics – resource-efficient land usage
- Car roof with high-efficiency solar cells and MorphoColor® colored layer
- Power yield prediction for large PV power plants

Photo: Stringer in the Module-TEC – Module Technology Evaluation Center of Fraunhofer ISE.

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

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Selected Projects in 2019

- WATERMED4.0 – Smart Technologies to Improve Quality and Safety of Mediterranean Agriculture
- SHRIMPS – Solar-Aquaculture Habitats as Resource-Efficient and Integrated Multilayer Production Systems
- Lade-PV – Development of Vehicle-Integrated Photovoltaics for On-Board Charging of Electric Utility Vehicles
- PV2Go – Solar Potentials of German Traffic Routes – Modelling, Measurement and Validation with Citizen Scientists
- KleVer – Cost-Saving Adhesive Based Connection Technology for High Efficiency Solar Cells
- CONNECT – Combined Metallization and Connection Technology for Efficient PV Modules

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

1

SmartCalc.CTM: Module Optimization with Digital Twins

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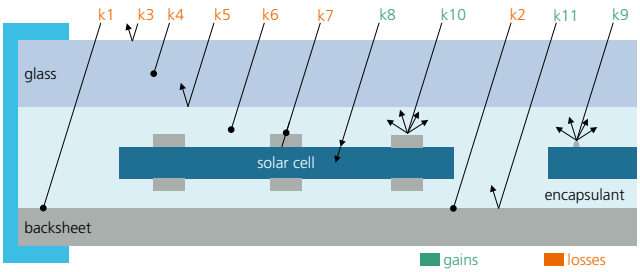
Although the analysis of losses in technical systems and their subsequent optimization is part of every development process, they are accompanied by a considerable effort for characterization, prototype preparation and detailed determination of the active loss channels. Simulation and digitalization allow for the significant reduction of development time and resources and the quick and simple identification of improvement potentials.

SmartCalc.CTM is a software which Fraunhofer ISE has developed to create virtual PV modules and analyze losses in performance and efficiency from the solar cell up to the complete module. The underlying detailed physical models for optical, electrical and thermal module behavior allow module performance to be predicted accurately. Starting from material parameters, a description of the module configuration and the operating conditions, the software analyzes module performance and provides an overview of losses and gains in the PV module.

"Digital twin" modules by physical-technical models makes it feasible to compare different module concepts rapidly with each other, vary individual technical parameters and carry out "what if" analyses or multi-dimensional optimization. The user-friendly interface to the software facilitates the input of characteristic data. The flexible models allow the development departments of materials, module and system producers to compare PV module designs for which no production equipment yet exists, for which it would be prohibitively expensive to produce prototypes or which should be used as references for comparison.

SmartCalc.CTM enables the analysis of many different types of technology and variants:

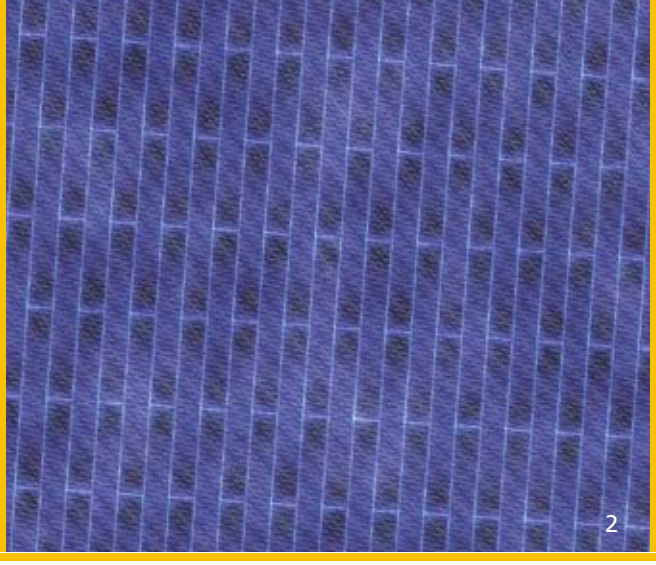
- monofacial and bifacial solar cells of different cell dimensions
- shingle connections, back-surface contact technology (MWT, IBC)
- half cells and full cells
- glass-backsheet, glass-glass or other module configurations and materials
- rectangular ribbons or round wires for soldered or adhesive connections



Graph: Optical gains and losses in a PV module.

The portfolio of models integrated into SmartCalc.CTM is continually being extended and now also allows the analysis of modules under relevant operating conditions. For example, irradiance, ambient temperature and wind speed can be varied. The models use these input parameters to calculate the module performance, taking the module configuration into account, and thus allow further analysis and optimization from the solar cell up to module operation (cell-to-system). A free trial version is available for download from our home page.

1 *SmartCalc.CTM – computer-aided module optimization.*



PV for Mobility: Solar Electricity from the Car Roof

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According to current estimates, more than 70 % of all vehicles newly registered in Germany in 2028 will have electric drive units, some of them within hybrid vehicles. Solar cells that are integrated into the vehicle can reduce the external electricity consumption and CO_2 emissions considerably and increase the range of electric vehicles noticeably.

The prototype of a highly efficient solar car roof that has been developed at Fraunhofer ISE represents a completely new approach, with its curved form and colored surface. The solar cells used are commercially available PERC solar cells, which today achieve efficiency values exceeding 22 % in series production and are inexpensively available on the market. The solar cells are cut into six strips with a laser process that causes little damage. The strips are laid in rows and each row slightly overlaps the following row, connected by an electrically conductive adhesive (ECA). The rows can also be displaced sideways with respect to each other. In this way, an electrically and mechanically connected matrix is created, with which modules of different dimensions can be covered completely and very flexibly. This so-called matrix shingle process allows for the significant reduction of losses of active area and resistance in a module compared to classic connection processes.

Matrix shingle modules have very high module efficiency, they feature an extremely homogeneous appearance, they show lower power losses under partial shading conditions and the connection is lead-free. In cooperation with materials and equipment producers, Fraunhofer ISE is developing adhesives, processes and equipment for shingle and matrix shingle technology.

For demonstration, a cell assembly based on matrix shingle technology was integrated into a commercially available, panoramic car roof made of curved glass. Already established production technology for car roofs was applied for the process. The MorphoColor® optical structure, which was developed at Fraunhofer ISE, covers the solar cells within the glass laminate and can be produced in many different, highly saturated colors. Compared to an uncoated glass cover, the transmittance loss due to MorphoColor® amounts to only 7 $\%_{rel.}$ on average. The combination of commercially available PERC solar cells, matrix shingle technology and the MorphoColor® coating is the ideal basis for cost-effective, aesthetically attractive products for integrated photovoltaics.

The power density of the photovoltaic car roof can reach about 210 W / m^2 and, using the typical roof area of a medium-sized car, the modules provide electricity for driving up to 13 km per day. The estimate is based on the solar radiation on a sunny summer day in Freiburg and a vehicle power consumption of 17 kWh per 100 km.

1 *Highly efficient but invisible solar cells in the car roof display good performance.*

2 *Shingled solar cells in a matrix configuration achieve very high efficiency.*

Agrophotovoltaics Significantly Increases Land-Use Efficiency

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An idea of Prof. Adolf Goetzberger, the founding director of Fraunhofer ISE, has taken a long time to be put into practice: Just on forty years after his paper on agrophotovoltaics (APV), the combination of photovoltaic electricity generation and agriculture on the same land, a clear global trend in this direction can now be recognized. National funding programs in Japan, China, France, the USA and most recently South Korea demonstrate that APV is not only technically and economically feasible but that it can be of appreciable additional benefit to agriculture.

Since 2014, Fraunhofer ISE has been investigating APV technology within funding programs of the German Federal Ministry for Education and Research (BMBF) and estimating the potential for Germany. In a test plant near Lake Constance, an increase in the land-use efficiency of up to 86 % and an improvement in agricultural resilience during dry periods have been demonstrated. The results also show the enormous potential of APV for arid climatic zones, where crops and farm animals can benefit from the shade provided by the PV modules. The specific yield of the PV system in 2018 was above average, with 1285.3 kWh per installed kW_p. If the levellized cost of electricity is calculated, the electricity from an APV plant is already competitive with small roof-mounted systems today. In addition, falling costs can be anticipated due to learning and upscaling effects.

PV roofing can be expected to provide additional benefits particularly for fruit and special crops which are particularly affected by the increasing risk of damage due to hail, frost and drought. Potential for synergetic effects between the PV and the agricultural sectors include the reduced need for irrigation, less wind-induced erosion, optimized lighting for field crops including the case of tracking systems, the dual use of the PV substructure to support protective nets or sheeting and the options to collect rainwater for irrigation purposes.

Increasing land scarcity, the growing demand for energy from renewable sources, falling module and system costs and the need to increase agricultural resilience mean that in future, agriculture and PV can also be conceived together in Germany.

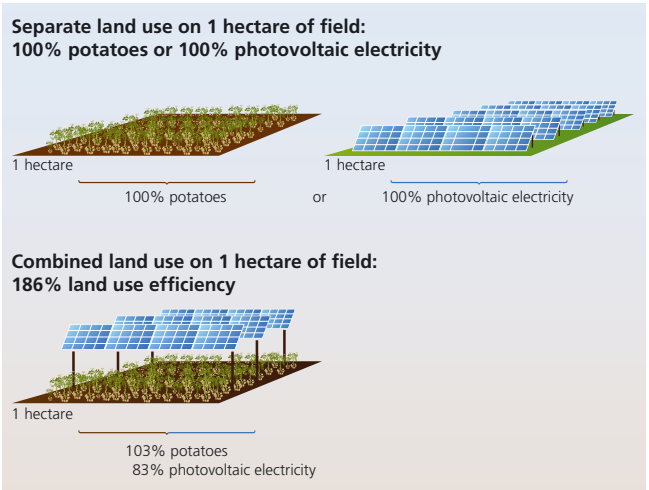

Illustration: Due to the combined usage, the land-use efficiency of the potato-growing APV system was 186 % in 2018.

1 *Agrophotovoltaic plant in Heggelbach near Lake Constance.*

Performance Analysis of Commercial PV Power Stations

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Based on the data from 44 PV power stations in Germany with a rated power between 500 kW_p and 1500 kW_p and an operating time of about ten years, Fraunhofer ISE has carried out a comprehensive performance analysis. Extensive quality assurance had been carried out in all of the investigated plants. Together with our partner, Pohlen Solar, we established quality criteria for selecting solar modules and tested various types of modules in our laboratories. In addition, we have calibrated power measurements from a selected random sample of all the module types that are installed in the plants. On the basis of the continually acquired data and the accurate measurement of solar irradiance with regularly calibrated irradiance sensors, well-founded information on degradation can be provided.

The most important conclusion from our work is that almost all of the observed degradation could be repaired or is reversible. This applies e.g. to inverter breakdowns or soiling of the PV modules. In addition, it became evident that in addition to climatic and location-specific conditions, operation management and maintenance have a significant effect on the observed yield losses. Inverter failure was the main cause for the fluctuations in the plants' performance ratio, which was large in some cases.

PV modules which were taken from the field after ten years of operation show very small deviations in performance compared to the original values. High-quality PV modules are very reliable and stable. Since the first power plants were commissioned in 2007, less than 0.25 % of the total of 200 000 modules had to be replaced due to defects.

Light soiling of the solar modules can be detected at almost all locations. In some projects, heavily soiled PV modules are present, usually due to bird droppings. Particularly in recent years, there have been longer periods in Germany with very little precipitation, so new cleaning strategies will have to be considered in future.

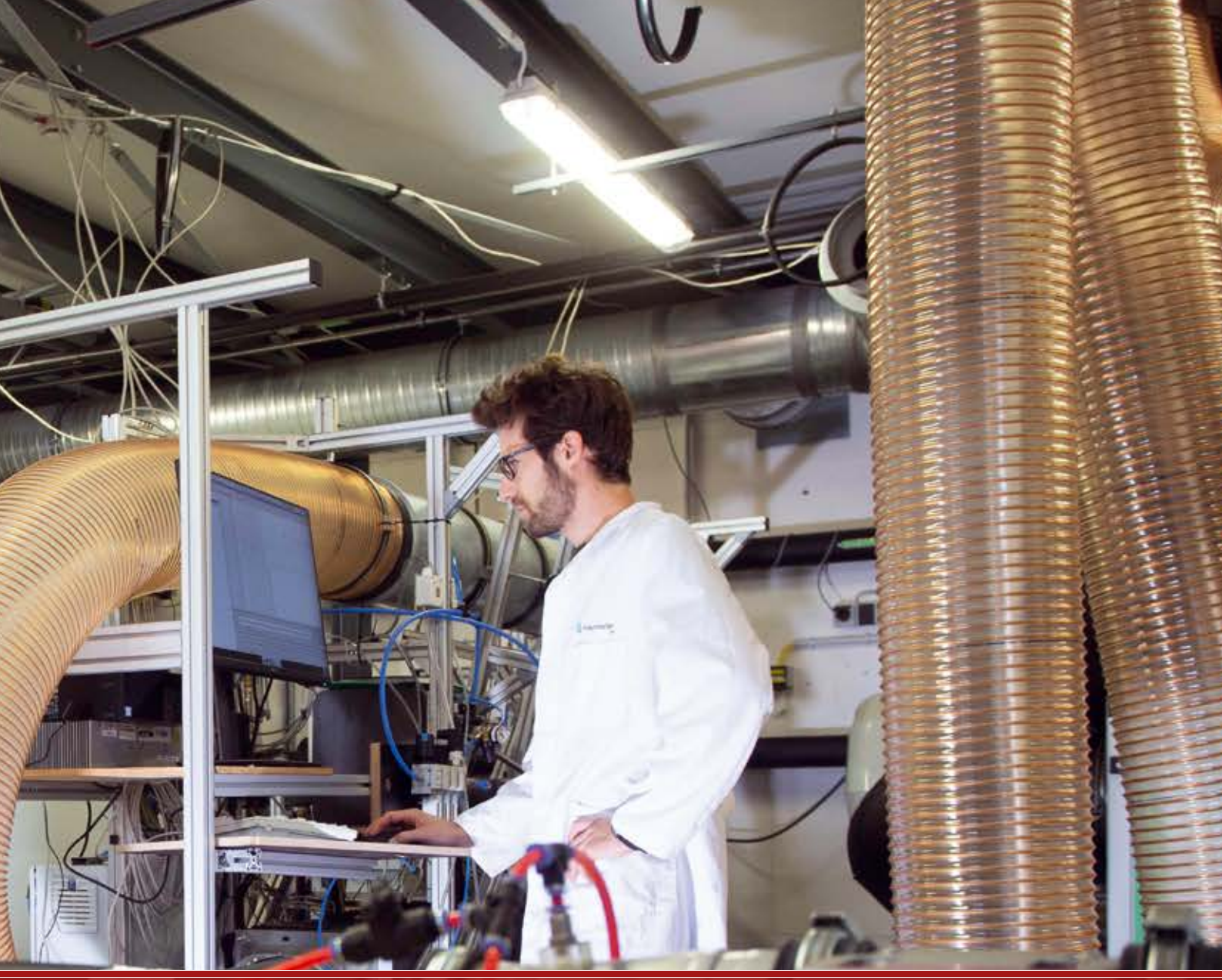
The results show that focussed quality assurance can significantly reduce technical risks and guarantees very high performance from commercially operated PV power stations. In future, digitalized processes will recognize system failures earlier and new approaches to maintenance concepts will clearly optimize the effort needed for operation of the plants.

1 *The PV power plant located at Altenstadt in Bavaria, Germany has been in operation since 2006.*

ENERGY TECHNOLOGIES AND SYSTEMS

Thanks to research and development as well as market dynamics, solar electricity has now become the cheapest source of energy. Further technological progress is underway. Photovoltaics and wind energy form the pillars of the energy transformation. Significant expansion of the corresponding installations in past years has resulted in the proportion of electricity from renewable sources having increased to 46 % in Germany in 2019. However, the sectors of heat, transport and industry are lagging a long way behind. For instance, buildings in Germany are still predominantly heated by natural gas and oil, and mobility is mostly based on fossil fuels. Consequently – in the next phase – comprehensive integration of renewable energy is on the agenda, simultaneously demanding much stronger sector coupling between electricity, heat and transport. There are many arguments to support greater electrification of all of these sectors. In numerous application areas, electricity that is increasingly being generated from renewable sources can be used directly very efficiently, e.g. in heat pumps or battery-equipped electric vehicles. Batteries for short-term storage play a central role, in mobility and for very diverse stationary applications from domestic storage units in connection with photovoltaic systems up to large-capacity storage facilities in renewable energy power plants. The development of adapted battery systems and their sustainable, safe operation are important R&D topics.

Photo: Test stands to characterize novel heat-transfer units of differing scales and construction forms for application in vehicles, building air conditioning and industrial processes.



Applications which are less accessible to direct utilization of electricity include heavy road transport, shipping, aviation and industrial processes. However, these can be supplied with renewable chemical fuels to an increasing extent. As biomass resources are limited, hydrogen will play a central role here, which can be used either by conversion back into electricity in stationary or mobile fuel cells or directly in industrial processes. Furthermore, hydrogen can be converted together with CO_2 to produce renewable synthetic fuels or chemicals for industry. Electrolysis thus assumes a key role in transforming renewable energy into chemical forms that can be stored readily. The utilization of the produced hydrogen ranges from applications in industry (chemical, steel) through the production of synthetic liquid fuels to the generation of electricity in fuel cells, particularly, but not only, for mobility applications.

Solar thermal processes allow the direct usage of renewable energy for heating applications or, in sunny locations, its conversion to cost-efficiently storable heat at high temperatures for electricity generation on demand. These technologies, with application areas lying mainly outside Germany and Europe, are also a focus of our work, as are water treatment and purification processes to enable the resource-saving usage of water.

Since its establishment, Fraunhofer ISE has worked on many technologies and questions which are now highly relevant in the current second phase of the energy transformation and are addressed in the "Energy Technologies and Systems" division.

ENERGY-EFFICIENT BUILDINGS

159
Total staff

15
Journal articles and contributions to books

51
Lectures and conference papers

8
Newly granted patents

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.

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 refrigerant 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 for both the use of fluctuating renewable energy sources in buildings and also for making the heating demand more flexible in order to increase grid-supportive building operation. Storage units for heating as well as for cooling applications are 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 life cycle of a building with a consistent semantic description. Error analyses based on artificial intelligence and their implementation in hardware and software guarantee a high-quality energy supply on the basis of renewable energy sources.

Our newsletter offers regular updates on our research milestones!

Photo: Fraunhofer ISE is conducting research on energy-efficient de-icing of the air units of heat pumps with heat from the ground.

Milestones in 2019

- SHK4Future exhibition container constructed with the participation of apprentices of the Richard-Fehrenbach-School and students of the Offenburg University of Applied Sciences to promote understanding of innovations in HVAC trades
- Hardware-in-the-loop test stand for Model Predictive Control for heat pumps taken into operation
- Prototype of a brine-water heat pump with only 150 g of propane as a refrigerant provides 8 kW of heating power and thus demonstrates the feasibility of indoor installation of heat pumps with natural refrigerants

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

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Selected Projects in 2019

KoST – Cost Optimization in Solar Thermal Energy by Means of Standardized Components and Interfaces

BIM4Ren – BIM Tools and Services for Building Renovation

EnEff2050Begleit – Competition and Project Support within the Framework of the Funding Initiative Innovative Projects for the Virtually Climate-Neutral Building Stock 2050

EnergieDigital – Integral Description of Building Services in BIM for Planning and Operation of Energy-Efficient Buildings

SHK4FutureEnergysystems – A Tiny House as a Mobile Showroom for Modern Building Technology

Thermal Fabric (Thermogewebe) – Technological Design and Thermal Fluid Dynamic Characterization of Wire Fabric-Based Micro Heat Exchangers with High Performance Potential

CRAVEzero – Cost Reduction and Market Acceleration for Viable Nearly Zero-Energy Buildings

WPVT-Freeze – Heating System Based on Heat-Pump Systems with PVT Collectors as Heat Sources

WPsmart im Bestand – Heat Pump Field Trial – Focus Existing Buildings and Smart Control

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

Heat Pump Systems for Existing Apartment Buildings

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In order for Germany to reach its political goals concerning climate change, the CO_2 emissions due to building heating must be greatly reduced. The application of heat pumps for heating technology is an obvious approach. Heat pumps are already commonly installed in newly constructed buildings. By contrast, their application in the major sector of the existing building stock is lagging very much behind, with an estimated share of 6 % (new installations). Apartment buildings are very much under-represented. Within our research on "LowEx in the Existing Building Stock", Fraunhofer ISE is cooperating with industrial partners to develop solutions to meet the specific challenges that apply here.

One of the technical difficulties is the limited availability of heat sources in apartment buildings. Thus, in the "Heaven" project, we are developing multi-source systems, which combine air and the ground as heat sources. As a result, the dimensioning and operation of the individual heat sources can be designed to be more flexible. The advantages include the regeneration of and reduced loads on the ground-based probes during periods when outdoor temperatures are high. In addition, the operating schedule of the outdoor air unit can be designed to reduce disturbance due to noise. In comprehensive laboratory tests, we demonstrated that it is feasible to de-ice the air unit with heat from the ground. The hydraulic coupling of the sources thus allows energy-efficient thawing operation.

Climate-Friendly Propane Heat Pump for Indoors

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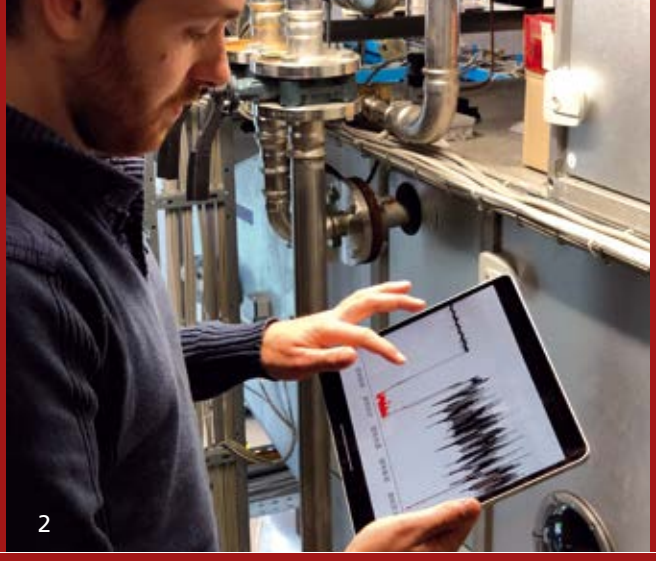
Heat pumps will be a central heating technology in future. However, currently most of them still use refrigerants with environmentally harmful greenhouse gases. According to the relevant EU regulation, refrigerants with a Global Warming Potential (GWP) exceeding 2500 will be forbidden already from 2020. Therefore, Fraunhofer ISE is conducting research on alternative, climate-friendly refrigerants for heat pumps. Propane has a GWP of 3 and is available inexpensively throughout the world, but it is flammable. If a heat pump for a single family house, with the usual power rating of 5–10 kW, contains more than the maximum permissible quantity of 150 g propane, the heat pump can be installed only if expensive and strict safety measures are taken.

Fraunhofer ISE has succeeded in constructing the prototype of a new ground-source heat pump which requires only a quarter of the refrigerant quantity compared to commercially available systems, while providing the same performance. A propane-based heat pump applying this principle would thus be the first in Germany which could be installed indoors in residential buildings without needing additional safety features. Containing 150 g of propane, it achieves a heating power of about 8 kW (operating point B0 / W35). Commercially available components were used for the prototype, which was designed to achieve a small filling volume of propane. The use of asymmetric plate heat exchangers and shortened pipe lengths were central approaches to achieve this goal, as most of the liquid refrigerant is located in these components.

1 *Deliberate ice formation in an outdoor heat pump unit in a laboratory experiment.*

2 *Prototype of the LC 150 Low-Charge Heat Pump in the Heat Pump Laboratory of Fraunhofer ISE.*



New Town Hall for Freiburg as a Net-Zero Energy Building

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The City of Freiburg has been operating its new Town Hall since the end of 2017 as one of the largest buildings (energy-serviced floor area of 23 000 m^2) in Europe with the net-zero-energy predicate. Based on a calculation at the primary-energy level, a net-zero energy building generates as much energy during one year as it consumes. The boundary for the primary-energy calculation, according to the German Energy-Saving Ordinance (EnEV), includes the energy demand for heating, ventilation, lighting, cooling and domestic hot water.

To compensate for the energy consumed by the Town Hall, almost the entire building envelope is used to gain energy via photovoltaics. To heat domestic hot water, combined photovoltaic-thermal (PVT) collectors with a gas-fired peak-load boiler are used. The low-temperature heating is based on heat pumps applying groundwater as the heat source, and cooling is achieved using a groundwater well. Heat and cooling energy are mainly transferred to the rooms via thermally activated concrete cores together with ceiling sails, so that the heating and cooling occurs with small temperature differences.

After one complete year of operation, an analysis of the monitored data by Fraunhofer ISE showed that the net-zero energy goal was almost reached in 2018. The potential for optimizing the operation of the heat pumps and the PV system was identified and its realization will already affect the balance for 2019 positively. In addition, dynamic load profiles for the energy demand and supply were investigated and options for a grid-supportive operating concept were elaborated.

1 *Town Hall "im Stühlinger" in Freiburg with façade-integrated photovoltaics and photovoltaic modules on the roof.*

Monitoring of Technical Building Services with Artificial Intelligence and User Feedback

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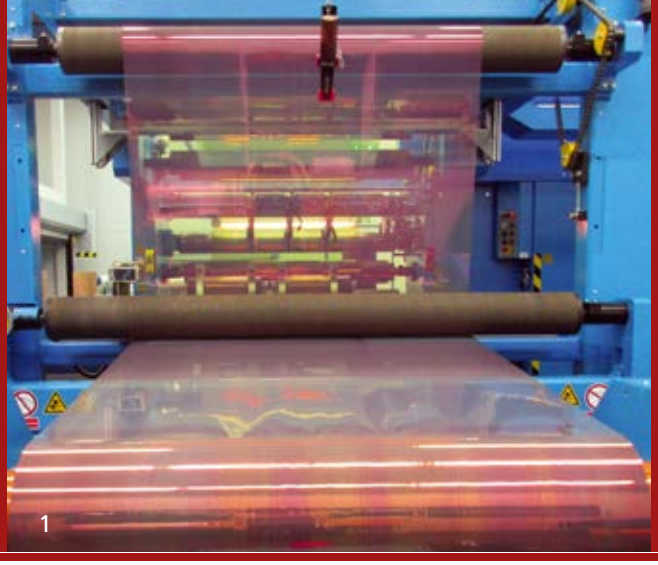
In many cases, technical building services are not operated optimally. Faults or sub-optimal operating modes can result in disproportionately high energy consumption, reduced comfort, premature wear in individual components and higher costs. For many years, methods based on measured data from relevant systems have been developed at Fraunhofer ISE, which automatically detect faults and unexpected deviations (outliers) and generate informative message to the system operators.

Now a patent claim has been lodged for a procedure which, on the one hand, applies artificial intelligence methods and, on the other hand, takes account of experts' knowledge to recognize faulty system conditions at an early stage. The project was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The procedure allows the automatic monitoring of the system operators immediately after commissioning, without long training and running-in phases, and the notification of the user, e.g. the facility manager, about unusual conditions. The user has the option either to confirm and react to identified faults and outliers or to reject them. The developed procedure uses this information to continually improve its accuracy and adapt it to prevailing circumstances, which may have changed after commissioning.

The procedure is conceived such that the required user feedback is minimal and rapidly diminishes during the course of operation, while the accuracy continually increases at the same time.

2 *Application of an adaptive procedure to detect a faulty operating condition in a cooling tower.*



Solar-Control and Low-e Coatings for Membrane Architecture

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Low-e and solar-control coatings represent the state of the art for windows and glazed façades. By contrast, large-area functional thin films are completely lacking in membrane architecture, which results in poorer energy efficiency for membrane-based buildings. Thus, Fraunhofer ISE is researching novel coatings for membranes.

In the "follow-e2" project that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), a product portfolio of coated ETFE films for membrane buildings in different climatic zones was developed in cooperation with the project partners, ROWO Coatings, Dunmore Europe, 2construct and HFT Stuttgart. As significantly harsher environmental conditions prevail in membrane cushions than in a fenestration system, the functional PVD coatings are combined with a protective lacquer. The functional PVD coating itself consists of a thin silver film which is embedded between adhesion and barrier layers. The stability of the coating systems when subjected to moisture, condensation, thermal cycles, salt mist and mechanical expansion was proven. In addition, the stability of the coated polymer films throughout the complete processing chain, from welding the coated membranes to form cushions, through transport, to installation at the building site, was positively accessed. Possible damage during the manufacturing process, such as deeper scratches, can be sealed with a repair lacquer that was identified within the project. The coating processes were upscaled to two production lines belonging to the project partners, ROWO Coatings and Dunmore Europe.

European Testing Standards for Heating Products under Investigation

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In order to increase the energy efficiency of buildings and thus achieve its political goals relating to climate change, the European Union has released a series of directives which place new demands on energy-consuming products. Equipment for space heating and domestic hot water plays a prominent role, as it is responsible for about one third of the end-user energy demand in the EU.

Independent evaluation and solidly based quality assurance of these products represent an important pre-requisite to ensure fair competition for new, energy-efficient technologies. This is guaranteed by standardized testing procedures. The underlying national and international testing standards, which are also specified in the relevant EU directives, such as the ecodesign or energy consumption rating directives, will be thoroughly revised in 2020.

Initially, the testing methods and standards will be validated within the EcoTest project in a series of inter-laboratory comparisons throughout Europe. Renowned, accredited testing institutes will then prepare proposals for improvement.

Fraunhofer ISE led the initiative for different types of electrically driven heat pumps, including hybrid heat pumps. In addition, we played a major role in the measurement of solar thermal collectors and systems and of gas sorption heat pumps.

1 *Roll of ETFE membrane with a sputtered coating and protective lacquer, in the roller unit at ROWO Coatings.*

2 *Accredited measurement of a heat pump in the TestLab Heat Pumps and Chillers.*

MorphoColor®: Stele to Demonstrate Colored BIPV Modules

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To realize the energy transformation, large areas will be needed for installation of the necessary photovoltaic modules. Sufficiently large areas with the potential for generating electricity are available on buildings. At many application positions, particularly when they are integrated into façades, it is important that the PV modules can be designed architecturally to meet requirements concerning urban planning and the architecture of the building. Simultaneously, the modules must deliver a high yield in order to improve the CO_2 balance of the building significantly and ideally reduce the energy balance to zero (net-zero energy building) or even make it positive (plus-energy building).

Fraunhofer ISE is conducting extensive R&D on building-integrated photovoltaics (BiPV). A new stele at the main entrance of Fraunhofer ISE displays different, highly efficient BIPV modules with the patented MorphoColor® colored coating and innovative shingle cells. The MorphoColor® colored coating is a photonic structure, in which an interference layer is combined with a geometrically structured substrate such that a narrow-band reflection peak results, which reflects only one specific color and transmits the remaining sunlight practically unimpeded. The design of the coating is inspired by the colored coating on the wings of the morpho butterfly, which feature an intense blue that remains apparently unchanged when viewed from a wide range of angles. Because the spectral band of the reflection peak is so narrow, the efficiency of the module is reduced by significantly less than 10 %-$_{rel}$. compared to that of a black module. The colored modules thus generate at least 90 % of the yield which would be provided by a black module at the same position.

A further innovation that is incorporated into these modules is the technology used to connect the individual cells electrically. The applied shingle technology allows the module area to be filled without gaps due to the overlapping cells, which increases the efficiency and results in a homogeneous black appearance without silver-metallic cell connectors. The uniform black appearance is the pre-requisite for the impression of homogeneous color, as reflective or glossy elements would disturb the color effect.

The stele thus demonstrates how innovative types of technology can contribute to solar-active building envelopes, becoming an obvious element for designing CO_2-neutral and architecturally attractive buildings.

1 *Pilot installation with MorphoColor® colored layers on the BIPV demonstration stele in front of the main building of Fraunhofer ISE in Freiburg.*

SOLAR THERMAL POWER PLANTS AND INDUSTRIAL PROCESSES

61
Total staff

10
Journal articles and contributions to books

11
Lectures and conference papers

1
Newly granted patent

Our newsletter offers regular updates on our research milestones!

Photo: Solar power tower plant at Ivanpah, USA. Fraunhofer ISE is working on the optimization of components, control, maintenance and operation of solar thermal power tower plants.

In sunny regions, solar thermal power plants based on Concentrator Solar Power (CSP) already provide electricity generated from a renewable source as demanded by applying 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 efficiency and reduce manufacturing costs. Cost-efficient and resource-saving operation of the systems is also the subject of the 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 specific 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 treatment. In addition to preparing drinking water from seawater or brackish water, we are working increasingly on purifying industrial wastewater or concentrating residual materials therein.

Fraunhofer ISE possesses profound expertise in materials science, component design, characterization and testing procedures, theoretical modelling and simulation, systems control and systems development. The Institute can draw on many years of experience from projects on applications in solar thermal power plants and in diverse industrial sectors. In our developments, we are directing our attention increasingly toward digitalization, Industry 4.0 and additive manufacturing.

Milestones in 2019

- New "ProLatent" heat-exchanger concept for thermal storage on the basis of phase change materials
- Successful field test of the new "HelioControl" control and calibration procedure for heliostats in solar thermal power tower plants
- Workshop to present results from the "RAISELIFE" project on detailed modelling of degradation and resulting optimization
- System prototypes to treat industrial wastewater delivered in the "ReWaCEM" project
- Training sessions and project preparation for solar process heat in the "Solar Payback" project
- Industrial workshop for the CSP industry in the SFERA-III project

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

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Efficient Heat Exchangers
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Selected Projects in 2019

- HelioGLOW – Development of Components for a Solar Thermal Power Tower Plant
- SFERA-III – Solar Facilities for the European Research Area – Third Phase
- ReWaCEM – Resource Recovery from Industrial Wastewater by Cutting Edge Membrane Technologies
- SOLSEC – Secondary Reflectors for Solar Power Tower Receivers
- AVUSpro – Automated in situ Measurement of Soiling for Site Assessment and During Operation of Solar Thermal Power Plants
- RAISELIFE – Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology
- Sinotrough – Parabolic Trough Technology for a Sustainable Energy System in China
- FENOPTHES – Development and Optimization of Filler Materials for Thermal Storage
- GeoSmart – Technologies for Geothermal Power Plants to Enhance Competitiveness Through Smart and Flexible Operation
- HelioControl – Development of a Camera-Based Calibration and Control System with Closed Control Circuit for Heliostat Fields

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

Life Cycle Simulation of Solar Thermal Power Stations

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Highly detailed system models are needed to optimize the operation of solar thermal power stations to achieve the highest yield possible. At Fraunhofer ISE, dynamic system simulations have been made with the "ColSim CSP" simulation environment already for more than 20 years. The component library has been continually extended with new components and functionalities. In recent years, we have extended the simulation environment to allow many years in succession to be simulated, such that aging processes of components and materials can be taken into account.

Solar thermal power stations are operated in arid regions in which water is often scarce. Thus, we have also integrated models for the water consumption in the power station, including the reflector cleaning, water and wastewater flows and water treatment, into the simulation. The properties of collectors or heliostats (e.g. the degree of soiling) can be modelled with spatial resolution in the solar field.

Simulations which take account of material degradation and detailed water management enable new approaches to optimize system operation and to evaluate the operating concepts on a techno-economic basis. For instance, we determine the optimal interval for re-coating tower receivers to minimize the levellized cost of electricity or investigate the savings achieved by recycling treated blow-down water for reflector cleaning.

3D Laser Scanning to Measure Heliostats in a Solar Array

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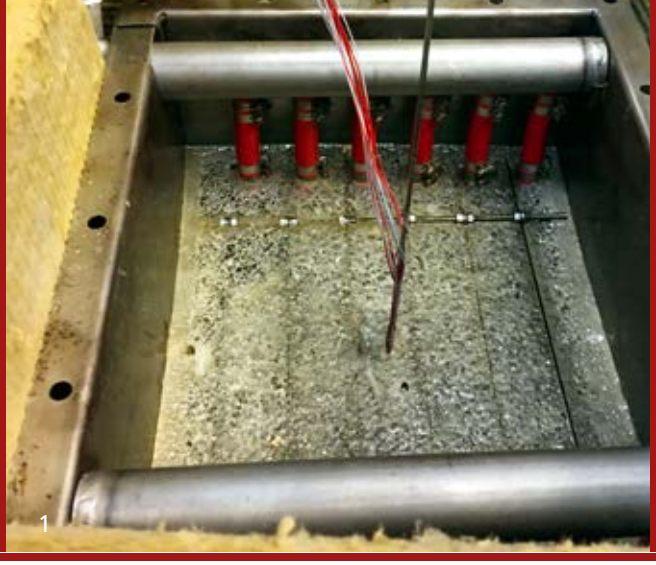
Heliostats are biaxially tracking reflector systems which concentrate sunlight onto a fixed receiver at the top of the tower in a solar thermal power system. The large distance to the receiver demands that the shape and position of the heliostats be controlled very accurately. The sub-structure for the reflectors, with areas of up to 150 m^2, affects the unit prices and the economic viability of the whole system.

Accurate measurement of the reflector form stability for different heliostat orientations can support the optimization of these structures. It is often very complicated to apply other techniques such as deflectometry or photogrammetry on-site at the solar array. Therefore, Fraunhofer ISE has cooperated with industry to develop another method: The reflectors are temporarily coated with spray-on chalk, which allows flexible measurements and measuring at many different positions with an accurate 3D laser scanner and a camera.

For example, a heliostat prototype with innovative composite reflectors was investigated within the EU-funded "RAISELIFE" project. The influence of gravity on the reflector form was measured for different orientations of the reflector between vertical (no influence) and horizontal (maximum influence). The analysis identified deformation of the sub-structure and bending of the reflector. The former had a large influence for these prototypes and can be improved in the next development stage.

1 *Detailed simulations are applied by Fraunhofer ISE to optimize the operating strategies of solar thermal power towers.*

2 *Measurement of a heliostat.*



Characterizing Heat Exchangers in Latent Heat Storage Units

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Fraunhofer ISE conducts extensive experimental characterization of heat exchangers in latent heat storage units. Our investigations focus on performance and efficiency. We utilize different phase change materials (PCM), ranging from water / ice mixtures to sugar alcohols, which melt at temperatures up to 200 °C. For characterization, temperature changes around the melting and crystallization temperature are induced at the inlet to the heat exchanger. We measure the resulting temperature profile in the PCM as well as in the return loop of the heat exchanger and analyze this with respect to its thermal performance. For example, we have investigated heat exchangers based on metal meshes and plates within the "Thermogewebe" and "ProLatent" projects that are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). Water / ice mixtures, paraffins and sugar alcohols were used as the PCMs.

In our experiments, we investigate heat exchangers that differ in materials and geometrical configuration and vary not only the PCM but also the mass flow through the heat exchanger and the range of the induced temperature change. The thermal performance, normalized to the heat exchanger area and the logarithmic temperature difference between the heat-exchange fluid and the PCM, is calculated from the measurement results. In this way, different types of heat exchanger technology can be compared to each other, evaluated and optimized.

Recovery of Acids and Salts from Industrial Wastewater

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The treatment and renewed usage of wastewater flows and processing fluids is the pre-requisite for closing material cycles in industry. When wastewater is treated to prepare fresh water, e.g. by reverse osmosis, very large proportions (> 90 %) of fresh water can be recovered. However, a highly contaminated, concentrated fluid remains. This problem is addressed within the "HighCon" project, which is funded by the German Federal Ministry for Education and Research (BMBF) and coordinated by the TU Berlin. Within this project, we have constructed a multi-phase demonstration system, with which a great range of industrial wastewater can be concentrated up to saturation levels and some salts can be selectively precipitated and reused. Among other aspects, we have developed an intelligent sequence of nanofiltration, electrodialysis metathesis and membrane distillation.

During surface treatment within the steel-processing industry, large amounts of acid-containing processing fluids are created, from which mixtures of water / residual acid / metal salts regularly have to be removed and disposed of. In the EU-funded "ReWaCEM" project, which Fraunhofer ISE is coordinating, systems based on diffusion dialysis and membrane distillation were developed, in which a large proportion (> 90 %) of residual acids can be recovered from wastewater concentrated and returned to the etching baths. To this purpose, we have constructed three systems to recover sulfuric acid from galvanization, hydrochloric acid from hot galvanization and HF-HNO_3 acid mixtures from stainless steel etchants and installed them in the field.

1 *View of an open latent-heat storage unit with plate heat exchangers (immersed in the PCM).*

2 *Demonstration system developed within the "ReWaCEM" project to recover acids and metallic salts from etching baths.*

HYDROGEN TECHNOLOGIES AND ELECTRICAL ENERGY STORAGE

145
Total staff

7
Journal articles and contributions to books

35
Lectures and conference papers

With our activities in this area, we offer R&D services addressing the generation, conversion and further thermo-chemical processing of hydrogen. Within the electrochemical generation of hydrogen, we are concentrating on the electrolysis of water in polymer-electrolyte membrane electrolysers (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 occur in practice. 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.

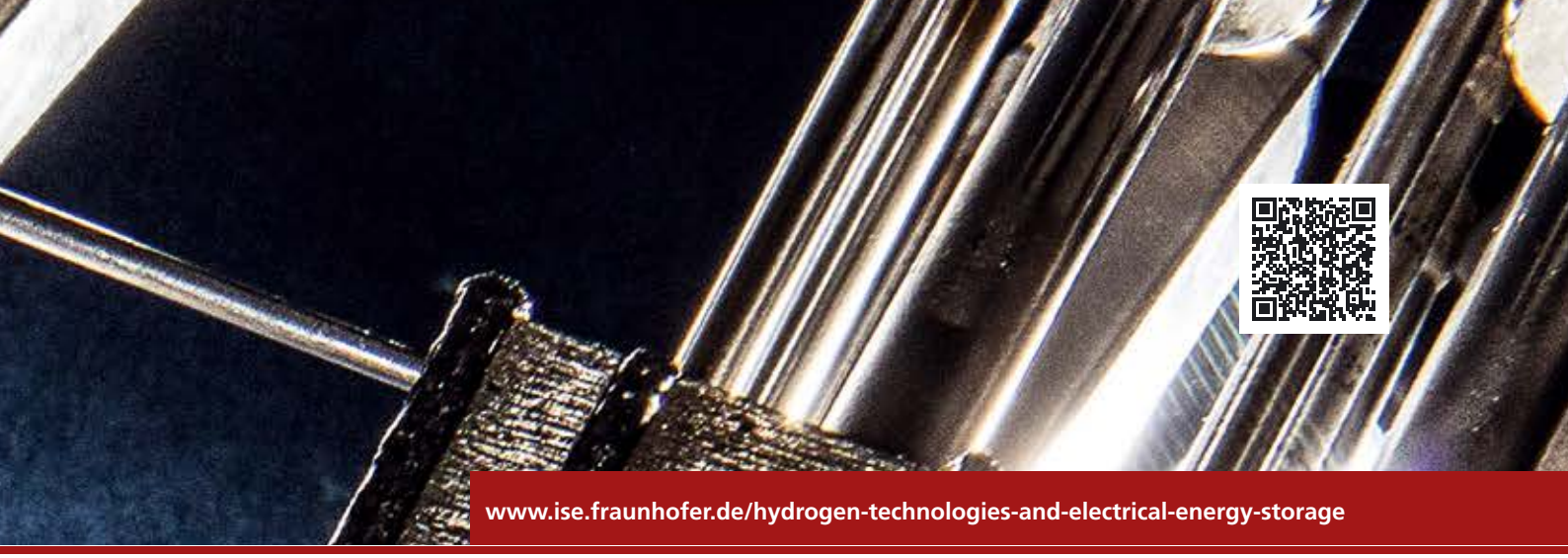
For battery materials, cells, modules and systems, we offer R&D services based on conventional and future technology. These encompass the analysis and exploration of new material combinations and cell architecture, the investigation of new manufacturing processes, the construction of battery cells, and their configuration and characterization. We analyze aging mechanisms and approaches to increase cycling stability and chronological lifetime. Accreditation of our battery testing laboratory by DAkkS (Deutsche Akkreditierungsstelle) is planned, so that from 2020 we will also be able to offer accredited measurements. We also develop complete 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.

Our newsletter offers regular updates on our research milestones!

Milestones in 2019

- Comparative study of greenhouse gas emissions from battery-equipped and fuel cell vehicles
- Start of the "LiBatt" joint research project on solid lithium batteries with non-woven fabrics, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi)
- Start of the "EMILAS" project on electromobility in apartment buildings with intelligent charging stations and second-life batteries, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi)
- Fraunhofer ISE is an important partner in the project started in 2019 to establish a research factory for battery cell manufacturing, funded by the German Federal Ministry for Education and Research (BMBF)

Photo: CATVAP (Catalytic Evaporation Process) in a stack configuration to reduce emissions and increase efficiency in combustion engines.



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

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Battery System Technology
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Applied Storage Systems
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Selected Projects in 2019

HAIMa – H2 and Cation Contamination – Aging Effects, Material and Sensor Development

DSW – Planning and Feasibility for Direct Solar Hydrogen Generation for Mobility

Lighthouse Project Power-to-Gas – Applied R&D for the Economical Hydrogen Production as Fuel based on Green Electricity

FrHyBus – Potential of Hydrogen Fuel Cell Buses in Local Public Transport in the Freiburg Area

LiteFCBike – Fuel Cell System for an Electric Carrier

EnStadt:Pfaff – Innovative Photovoltaic DC Charging Infrastructure with Buffer Storage

Kopernikus-Projekt Power-to-X – High-Quality Applications: Storage, Distribution and Use via Liquid Organic Hydrogen Carrier (LOHC)

Rural-Li – Robust Lithium Battery Storage for Use in Isolated PV Systems of Low Power

REACT – Renewable Energy for Self-Sustainable Island Communities

EMILAS – Electromobility in Apartment Buildings with Intelligent Charging Stations and Second-Life Batteries

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

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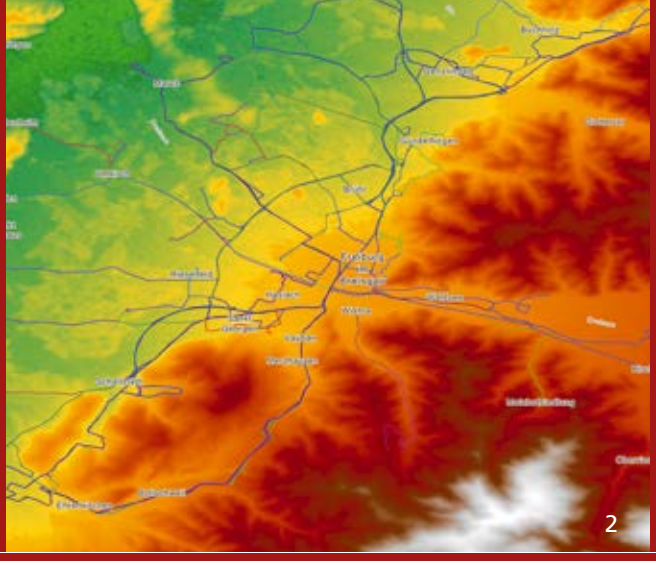

2

GIS-based Evaluation of Hydrogen and Power-to-Gas Infrastructure

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The increasing proportion of electricity in the grid from fluctuating renewable energy sources and the demand for renewably generated energy in sectors such as industry and transport mean that the need is increasing for a fuel which can connect these sectors to each other. Hydrogen can meet these requirements to a large part. As a result, the question of an optimal concept for the hydrogen infrastructure in Germany has arisen, accompanied by the selection of suitable locations for hydrogen systems.

In addition to its established work addressing the conceptualization, dimensioning and techno-economic evaluation of hydrogen systems (electrolyzers, power-to-gas systems, hydrogen filling stations), Fraunhofer ISE is thus currently developing a new tool to evaluate and optimize system locations and hydrogen infrastructure. A further application is the analysis of existing bus and train routes with respect to their potential suitability for using emission-free drive units.

For example, the tool allows GIS-based analyses to be used to identify the bus and train routes within a certain area, such as that of a regional transport association, which would be suitable for utilizing fuel cell drives. To evaluate the routes, previously defined parameters, e.g. the total daily distance covered, gradients and the number of stops, are taken into account. On this basis, the suitability of each route is determined.

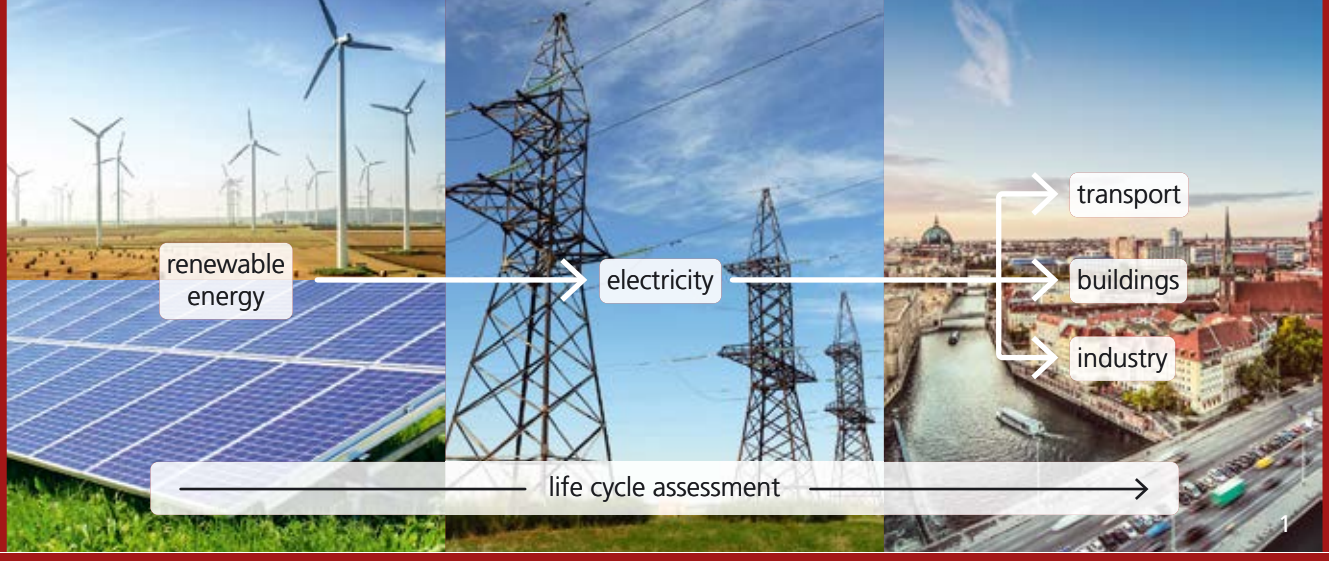
This allows for the determination of the maximum technically accessible potential of a whole region. In a similar way, the tool can also be used to analyze and optimize complex hydrogen supply routes, consisting of H_2 generation, transport and consumption systems.

With the help of the "H_2ProSim" (hydrogen process simulation) toolbox, which was developed by Fraunhofer ISE and has been successfully applied since 2012, the technical potential analysis can be complemented by an economic evaluation, from which a cost-efficient complete solution can finally be derived. This also makes simulation-based techno-economic analysis of different scenarios feasible. The definition of each scenario can be adapted individually to the requirements of the client and the specific project. This type of techno-economic analysis provides optimal preparation for a possible investment decision later.

Fraunhofer ISE thus has the opportunity to support industrial clients in dimensioning and site selection for electrolysis systems and in opening up new application areas. In the "FrHyBus" project, which is funded by the State Ministry for the Environment, Climate and Energy Economy in Baden-Württemberg, Fraunhofer ISE is cooperating with its partners, the City of Freiburg, Südbadenbus and the Freiburger Verkehrs AG (Transport Authority), to currently apply the tool and analyze the potential for hydrogen-based fuel cell buses for public transport in the greater Freiburg area.

1 *Hydrogen-based fuel cell bus from the Belgian manufacturer van Hool, in Cologne, Germany.*

2 *Assessment of public transport bus routes in the greater Freiburg area in Germany.*



Life Cycle Assessment of Processes for Sector Coupling

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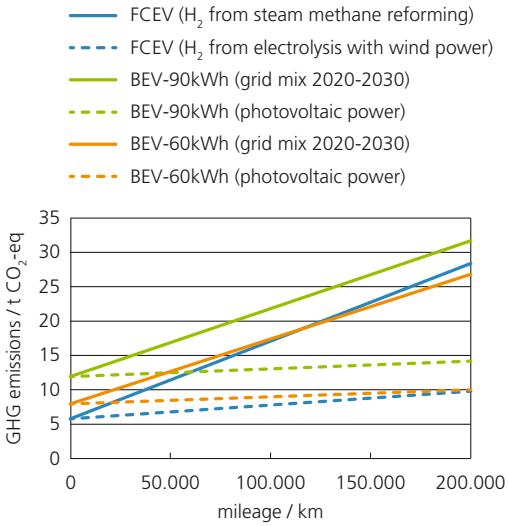
Renewable sources of energy must be used in all sectors (electricity, buildings, transport, industry and agriculture) for the climate-change goals to be reached. To date, the integration of renewable energy has advanced furthest in the electricity sector. For this reason, the usage of electricity from renewable energy sources is also being discussed at present for the transport, buildings and industry sectors (Power-to-X). Some applications, such as electric vehicles or heat pumps, can use electricity directly. Other applications, such as in the chemical industry, require electricity-based fuels as substitutes for fossil raw materials. To obtain electricity-based fuels, initially hydrogen is produced by electrolysis. The hydrogen can be applied directly as a fuel or can be converted, e.g. by addition of carbon dioxide, to form synthetic chemicals and fuels such as methanol, dimethyl ether (DME) and oxymethylene ether (OME).

At present, numerous synthetic fuels with different advantages and disadvantages are being discussed. Therefore, Fraunhofer ISE is analyzing these synthetic fuels from a holistic perspective. The fuels are evaluated ecologically for a wide variety of scenarios, applying the method of life cycle assessment (LCA). In addition, different production variants are evaluated economically. In its holistic evaluation, Fraunhofer ISE profits from its many activities along the entire processing chain for synthetic fuels (e.g. photovoltaics, electrolysis, chemical synthesis in mini-plants and the "REMod" energy system model).

1 *The idea of Power-to-X: Generation of electricity from renewable energy sources and utilization of the renewable electricity in the transport, buildings and industry sectors.*

In addition to synthesizing fuels, Fraunhofer ISE analyzes their utilization. In an LCA short study for H_2 Mobility Deutschland GmbH & Co. KG, the usage of hydrogen in a fuel cell vehicle was compared to that of a battery electric vehicle, concentrating on greenhouse gas emission. The focus of the study was on large cars (suburban utility vehicles – SUV) with a range exceeding 300 km. The results show that a fuel cell electric vehicle has the potential to reduce greenhouse gas emissions compared to a battery electric vehicle with a large battery (>60 kWh). The fuel cell vehicle profits from lower greenhouse gas emissions during the production phase. By contrast, battery electric vehicles with a smaller battery capacity display advantages with respect to greenhouse gas emission. Additional aspects such as second life are to be considered in further investigations.



Graph: Greenhouse gas emissions as a function of mileage for fuel cell electric vehicles and battery-equipped electric vehicles with 60 kWh and 90 kWh battery capacity.

Electricity Supply of Islands by Intelligent Storage Design

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The cost of the electricity supply in regions remote from the grid or on geographical islands can be many times higher than from the public grid. In diesel-backed systems, fuel transport is the main cost factor whereas for the grid connection of an island, it is the expensive underwater cable.

Thus, the integration of renewable energy sources, which has become continually cheaper, has been technically and economically reasonable for years. However, with a growing proportion of fluctuating energy sources, intelligent and rapid control systems, as well as the integration of stationary storage systems, are essential for the electricity supply always to meet the demand profile and to ensure system stability.

These central topics are the focus of the "REACT" project within the Horizon2020 program, in which Fraunhofer ISE is playing a leading role in revising the supply strategies of eight European geographical islands, planning the required storage capacity and developing and implementing optimized control strategies for the battery storage units. The goal is to maximize the solar fraction and thus minimize the supply costs and CO_2 emissions.

Implementation of a central ICT platform, which is based on open-source energy management systems that were developed at Fraunhofer ISE, will make new business models feasible, in which both customers and grid operators can further optimize the utilization of installed storage units and other flexibility options.

Solar-Assisted Drying and Cooling Technology

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In many developing countries, the issue of preventing post-harvest losses by better cooling and drying of foods is important. In regions without grid connection, self-sufficient electricity supplies are often used for this purpose, using photovoltaic systems combined with suitable storage technology. Fraunhofer ISE is conducting research to guarantee a complete and reliable power supply by solar energy for these applications.

In Kenya, for example, we are cooperating with a German company, two Kenyan research institutes (KIRDI, KMFRI) and a Kenyan University (TUM) within a project for fishing communities. The natural fishing resources are shrinking, so that local Kenyan fishermen are dependent on fluctuating seasonal catches. The lack of suitable processing technology (cooling, storage, drying) forces the fishermen to sell their products very quickly and only in the nearby region – often at uneconomic prices.

In this context, Fraunhofer ISE is developing a technological package within an interdisciplinary project for processing the fish by cooling and drying, applying renewable energy sources. Ice chips, which are produced by a photovoltaically powered ice-making machine, are used to cool the goods. A solar thermal drying unit forms the basis for dehydrating the fish. This type of project with Fraunhofer ISE is also accompanied by local training and qualification measures.

1 *View of La Graciosa on Lanzarote, Canary Islands (Spain).*

2 *Typical fishing boats on Lake Victoria, Kenya.*

Solid-State Lithium Batteries with Sulfide-Based Ionic Conductors

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An increase in the energy density and safety of lithium batteries is of key importance for the successful transformation of the transport sector. Batteries with solid, non-flammable electrolytes (so-called all solid-state batteries) can contribute decisively to achieving this goal. The energy density can be increased particularly by using metallic lithium at the negative electrode. The solid electrolyte suppresses the feared formation of dendrites, which can lead to cell failure if liquid electrolytes are used.

Sulfidic ionic conductors feature high conductivity and ductility and can be processed at relatively low temperatures. Thus, they are also suitable for printing processes. At present, printing pastes and printing processes for the production of lithium batteries are being developed at Fraunhofer ISE, which are used to produce battery cells for subsequent characterization.

One active research topic is the investigation of the effect of the binder and dispersing agent on the conductivity of the ionic conductor and the performance of the complete battery cell. We make comparisons to batteries produced from pressed powders and pay particular attention to the interfaces between individual components, i.e. the electrochemically active materials and the sulfidic ionic conductors. We optimize these interfaces further by customized nano-technological coatings.

1 *Glovebox for preparation of sulfide-based solid-state batteries.*

Aging Investigations of Lithium-Ion Battery Systems

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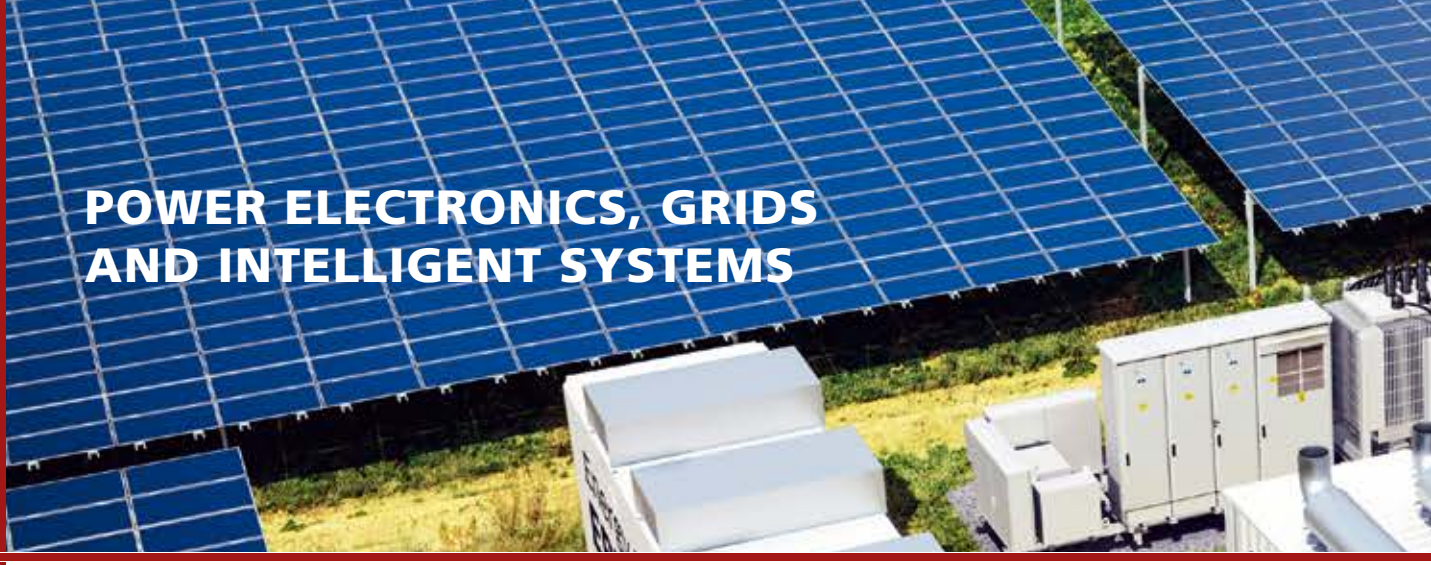
Battery storage units are being used increasingly often in stationary applications. They are often constructed of lithium-ion cells, for example, if large numbers of cycles and long chronological lifetimes are needed. However, the investment in these electricity storage units will only be amortized if it can be guaranteed that they operate safely and reliably in the application and the promised performance characteristics and lifetimes are achieved.

In its battery laboratory, Fraunhofer ISE carries out extensive aging investigations on both battery cells and complete battery storage units. We are not restricted to certain applications and are able to measure both stationary storage units for houses, commercial and industrial applications and also complete vehicle batteries. The operating parameters such as temperature, current and charging depth are varied during the measurements. On this basis, we develop aging models for different types of technology, with which technical questions concerning lifetime in specific applications can be answered and life cycle cost analyses can be prepared by conducting simulation studies.

The models are continually being developed further and parametrized and validated with measured data from our battery laboratory. In the "Safety First" and "Rural-Li" projects, for example, extensive aging tests are conducted. These form the basis for success within the "EMILAS" project, which has just started, addressing the application of second-use storage units in charging stations for electromobility, among other aspects.

2 *Investigating the lifetime of PV residential storage units in the battery laboratory of Fraunhofer ISE.*



POWER ELECTRONICS, GRIDS AND INTELLIGENT SYSTEMS

167
Total staff

21
Journal articles and contributions to books

35
Lectures and conference papers

2
Newly granted patents

In its work on Power Electronics, Grids and Intelligent Systems, Fraunhofer ISE addresses the digitalization of the electricity sector. We are working on optimizing the interaction between efficient generation from renewable sources, reliable supply for consumers, energy storage and stable operation of future electricity grids. Systems analysis for sectoral coupling – addressing the transport, heat and building sectors, represents another important focus of our activities.

Power electronics is becoming an increasingly important technology for the future energy supply, as it has to take on an increasing number of tasks to ensure grid stability. By applying the most recently developed components, such as semiconductor components of silicon carbide or gallium nitride, we are developing significantly more compact, more efficient and less expensive inverter systems. The increasing 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. Grid-supportive operation is based on both the observation of required grid codes and the optimal integration of the components mentioned above into the energy market.

Digitalization plays an increasingly important role in this process. In addition to simulation and optimization of electricity grids to achieve a greater capacity for fluctuating sources of renewable energy, we are also researching novel information and communications technology, including artificial intelligence methods. Our goal in the context of smart grids is to link power plants and retain the resilience of the system while significantly increasing the proportion of renewable energy. 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 in the regional, transnational and political contexts.

Our newsletter offers regular updates on our research milestones!

Milestones in 2019

- Fraunhofer ISE "Energy Charts" extended with new functions and diagrams
- Official opening of new premises for the Center for Power Electronics and Sustainable Grids
- Multi-megawatt solar inverter with new functions for grid management tested
- 15 kV rail-transport inverter
- New study published on "Wege zu einem klimaneutralen Energiesystem – Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen", ("Paths to a Climate-Neutral Energy System – The German Energy Transformation in its Social Context"), based on "REMod" simulations

Photo: Hybrid power station consisting of a PV system, an energy buffer unit (EBU) and a diesel generator (GPU).

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

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Energy Systems Analysis
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Selected Projects in 2019

- LUIZ – Power Electronics – Intelligent and Reliable
- InteRessE – Resource Demand for the Energy Transformation: Interdisciplinary Evaluation of Scenarios to Supply Electricity and Heat
- OVRTuere – Over Voltage Ride Through – Temporary Overvoltages and Derived Rules for Efficient and Safe Grid Operation
- WARO – WeatherAggReOpt
- GeoSmart – Technologies for Geothermal Power Plants to Enhance Competitiveness Through Smart and Flexible Operation
- EnStadt:Pfaff – Innovative Photovoltaic DC Charging Infrastructure with Buffer Storage
- Q-Integral – Reactive Power Management in Use with Dynamic Reactive Power Sources at the Interface of Distribution Grid and Transmission Grid
- REACT – Renewable Energy for Self-Sustainable Island Communities
- IEK – Development of an Integrated Energy Concept for 2050

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

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Impedance Spectroscopy of Inverters

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Harmonic disturbance can endanger the stable operation of PV and wind parks. Often it is caused by a resonance-based interaction between inverters and the grid, which cannot be detected by the established procedures to evaluate the harmonics created by inverters alone.

With the so-called impedance spectroscopy of inverters, Fraunhofer ISE has developed a new characterization procedure, with which both the internal harmonic sources of an inverter and its effective output impedance can be determined by measurement. To do so, the inverter to be tested is excited in a frequency range of up to 20 kHz with a variable small-signal voltage. After analyzing the measured current reaction, the inverter can subsequently be described as a frequency-dependent voltage source with internal impedance (a so-called Thévenin equivalent).

Using the result of the impedance spectroscopy, the resonance tendency of PV or wind parks can be analyzed by comparing the determined impedance profile of an inverter and a given grid connection point. Thus, a helpful new analytical procedure is now available to ensure high voltage quality when electricity grids are penetrated by an increasing number of inverters.

1 *Test stand to carry out impedance spectroscopy of inverters with a power rating of up to 1 megawatt.*

Charging Systems for Tomorrow's Electromobility

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High availability and grid-supportive services are very important for the integration of electric vehicles as intelligent consumers and storage units into electricity grids. In the "BiLawE" project, a bidirectional inductive charging system was developed and its economic integration into the electricity grid was investigated, accompanied by the development of corresponding business models. Incorporation of inductive charging infrastructure into various use-cases such as public parking areas, company car parks and smart homes allows convenient charging without a cable; the vehicle thus remains available more often and longer in the electricity grid, even when the battery is fully charged.

Furthermore, Fraunhofer ISE is developing very compact and highly efficient power converters, which are able to provide control power, reactive power and other system services in both directions. A particular challenge is posed by the requirement for low grid perturbation (total harmonic distortion THDi), as well as the feasibility to deliberately compensate harmonic resonance currents from non-linear loads in the grid and thus improve the voltage quality at the grid connection point.

We are also developing charge management, which provides a wireless connection between a vehicle and the infrastructure and optimizes the charging process within the local electricity system of the building or the grid sector. For the communication, we apply the international standard ISO 15118, which we have extended for wireless energy transfer and electricity supply back into the grid.

2 *Charging station at Fraunhofer ISE.*

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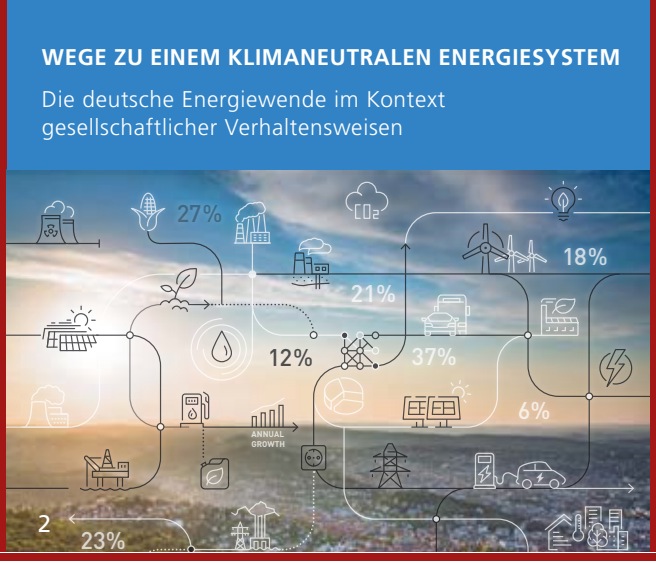

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Resource Evaluation for the Energy Transformation

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The transition from a fossil to a renewable energy system demands the utilization of many raw materials that are required for the production and maintenance of the applied energy technologies. Fraunhofer ISE investigates the demand for these raw materials and identifies possible supply risks, so that strategies to prevent resource shortages can be developed.

Fraunhofer ISE analyzes the supply criticality of raw materials not only at the global and national level but also for private enterprises. The demand for raw materials for industrial processes or technology such as PV modules, batteries, hydrogen technology and power electronics is identified and its criticality investigated. In doing so, we take account of raw material characteristics such as supply risks and environmental effects on the basis of their ecological balance, recycling potential, prices and social factors, and predict their development.

Our studies can be used both as a basis for strategic business decisions and to accompany the development of a product. We also consider the functionality of the individual raw materials in a product and identify designs that are optimized with regard to resource strategies. We validate these on the basis of an ecological balance and criticality analysis. For example, concept drafts for PV inverters are continually investigated with regard to critical resources and ecological questions, to obtain a final product that is optimized with respect to efficiency, reliability, costs and incorporated raw materials.

1 *Different critical or even toxic metals are applied in energy technologies.*

Paths to a Climate-Neutral Energy System

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Designing a sustainable energy system for Germany demands careful planning. It is important to take account of the challenges and synergetic effects which arise from the coupling of the electricity, heat, industry and transport sectors. To implement this transformation as cost-effectively as possible, while still respecting the climate protection goals of the German Federal Government, Fraunhofer ISE has developed the "REMod". It can be used to analyze the coupling effects, which occur by the simultaneous optimization of all relevant sectors and technologies of the energy system, and derive recommendations for action.

In the current study on "Paths to a Climate-Neutral Energy System – The German Energy Transformation in its Social Context" (Wege zu einem klimaneutralen Energiesystem – Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen) that is based on REMod, Fraunhofer ISE develops different self-consistent scenarios for redesigning the energy system. These scenarios are analyzed by taking diverse further developments of the model into account, which have been accomplished since the preceding study "How much does the energy transformation cost?", and recommendations for action are derived. In contrast to previous studies, a reduction of energy-related CO_2 emissions of 95 % or 100 % is considered.

On the one hand, the evaluation focuses on the role of photovoltaics for the energy system. On the other hand, we investigate which expansion of selected key technologies is needed to meet the climate protection targets in 2030 and 2050.

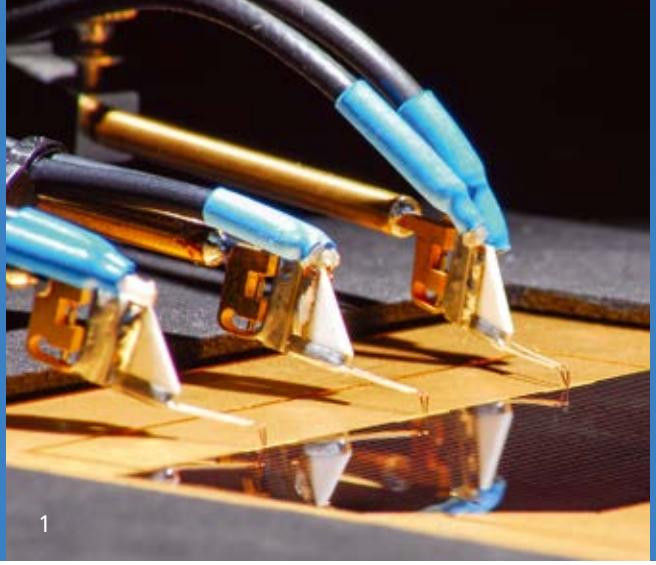
2 *The study "Paths to a Cimate-Neutral Energy System" was presented in February 2020.*

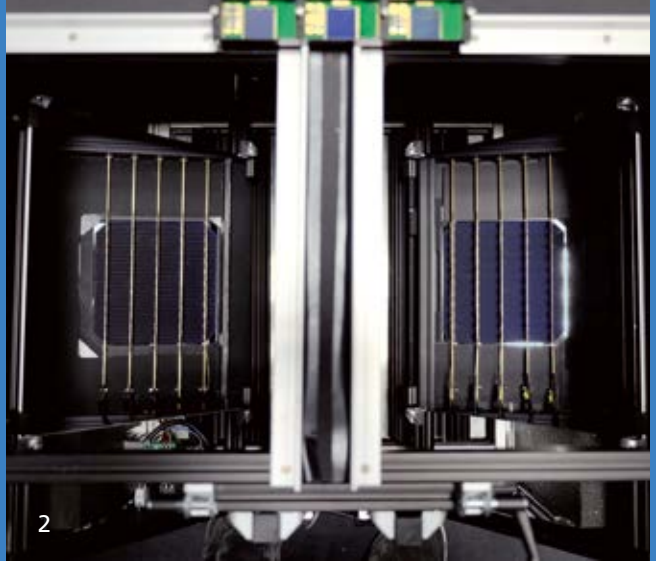
ACCREDITED LABORATORIES

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

Photo: Programming PV simulators for inverter tests in the TestLab Power Electronics.





Calibration of Solar Cells

cells@CalLab.de

CalLab
PV Cells

CalLab 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 technology. It is one of the internationally leading photovoltaic calibration laboratories and serves as a reference for research and industry. Solar cell manufacturers commission us to calibrate their reference solar cells for production lines according to international standards.

CalLab PV Cells is accredited as a laboratory for solar cell calibration with the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body). 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.

Bifacial solar cells can be measured accurately in our laboratory with either both surfaces or only a single surface being illuminated. Further development of our existing test rigs have enabled still greater accuracy and short measurement times, so that we can further improve services for our clients. Newly developed and improved optics play an important role for homogenization. Similar further developments are expected to also improve the measurement of large-area multi-junction solar cells in the near future. Various multi-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 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.

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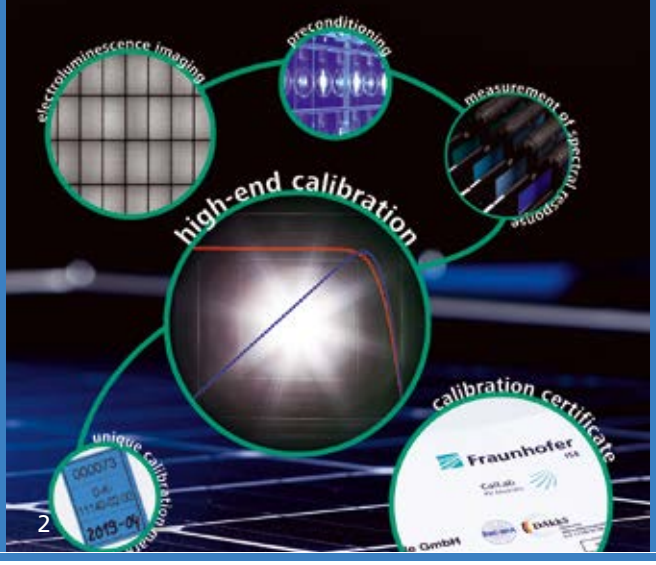
Wendy Schneider
Phone +49 761 4588-5146

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
- Solar cell calibration according to IEC 60891 and the standards of the IEC 60904 series under diverse reference conditions such as:
  - AM 1.5g (IEC 60904-3)
  - AM 0 (ISO 15387)
  - AM 1.5d (ASTM G173-03)

1 *Contacting during the calibration of a bare 4" space multi-junction solar cell.*
2 *Test rig to measure bifacial solar with either single-surface or bifacial illumination.*



Calibration and Performance Tests of PV Modules

modules@CalLab.de

CalLab
PV Modules

In our accredited calibration laboratory, we calibrate PV modules for production lines around the world accurately, quickly and reliably. With a measurement uncertainty of only 1.1 %, the reference products are calibrated for module manufacturers and thus provide the references for production quantities on the GW scale. Our calibration certificates and calibration marks on the modules stand for the highest accuracy and quality.

High-efficiency cell technologies such as PERC, TOPCon and HJT are currently being adopted by almost all module manufacturers, as are bifacial technologies. Continuous development of new measurement methods and adapted measurement systems in our calibration laboratory ensure that we can offer accurate power measurements for these PV modules.

With our accurate performance tests according to IEC 61853, we determine the module performance for relevant operating conditions with the lowest measurement uncertainty possible. By optimizing the solar simulators for power-rating measurements, we have further improved the accuracy particularly for low light levels. This measure significantly reduces the uncertainty of PV yield simulations and thus provides more certainty for investors in PV power plants. Based on our accurate performance tests in the calibration laboratory, we can carry out yield simulations for modules according to IEC 61853. In this way, different types of modules can be compared very exactly for given locations.

We can measure the power output from concentrator PV modules (CPV) under standard conditions using several outdoor test rigs equipped with trackers or in our laboratory with a solar simulator.

Frank Neuberger
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Standards and Specifications

- Accredited calibration laboratory according to DIN EN ISO / IEC 17025
- Calibration of PV modules with a measurement uncertainty of only 1.1 %
- Determination of the spectral response at the module and cell level from 300 nm to 1200 nm
- Accurate power rating measurements according to IEC 61853
- Simulation of module yields based on IEC 61853
- Evaluation of CPV modules according to IEC 62670-3 under CSOC and CSTC

1 *Inspection of a PV module before calibration.*
2 *Calibration procedure at CalLab PV Modules.*

Quality Assurance of PV Modules

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TestLab
PV Modules

Daniel Philipp
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TestLab PV Modules tests the quality and reliability of PV modules. Our accredited laboratory is equipped with modern and innovative testing facilities that can be used for applications that are not covered by 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 benchmark or assess the suitability of a specific type of module for particular application conditions.

To take the special technical features of new technologies (e.g. bifacial modules) into account, we participate in the further development of testing standards. We apply innovative and recently developed analytical methods to systematically investigate defects such as back sheet chalking and light and elevated temperature induced degradation (LeTID). TestLab PV Modules offers specific tests and test sequences for many typical defects. Our modern testing equipment provides extremely accurate measurement values.

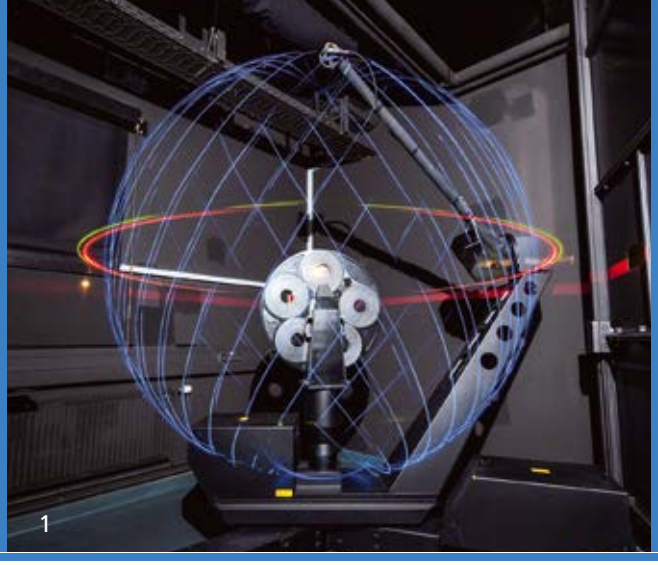
Very accurate power measurements are carried out in our accredited calibration laboratory, CalLab PV Modules, with an internationally leading measurement uncertainty of only 1.1 %. In cooperation with our partner, the VDE Prüf- und Zertifizierungsinstitut, we certify modules according to international 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, so that PV modules and components can also be operated reliably in these regions.

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 tests
  - Investigation of light and elevated temperature induced degradation (LID / LeTID)
  - Qualification of materials and components
  - Damage and failure analysis

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 Building Components

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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.

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Standards and Specifications

- Accreditation according to DIN EN ISO / IEC 17025
- Transmittance, reflectance and g value according to DIN EN 410, ISO 9050, DIN EN 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 *3D-scanning photogoniometer for angle-dependent optical measurements.*
2 *Outdoor Test Facility for Real-size Building Envelope Elements (OFREE).*

Testing of Collectors, Storage Tanks and Systems

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TestLab
Solar Thermal Systems

Integrated system solutions with the highest possible share of energy from renewable sources are essential to reduce CO_2 emissions. To ensure that technologies can be evaluated according to this criterion, it is necessary to have relevant technical coefficients, which Fraunhofer ISE provides to its clients. The portfolio of TestLab Solar Thermal Systems covers all types of solar collectors and thermal storage units as well as complete systems for space heating and domestic hot water.

Approval for the market introduction of PVT 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. storage 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. We carry out factory inspections for our clients around the world within the Solar Keymark certification program.

In situ measurement
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Collectors
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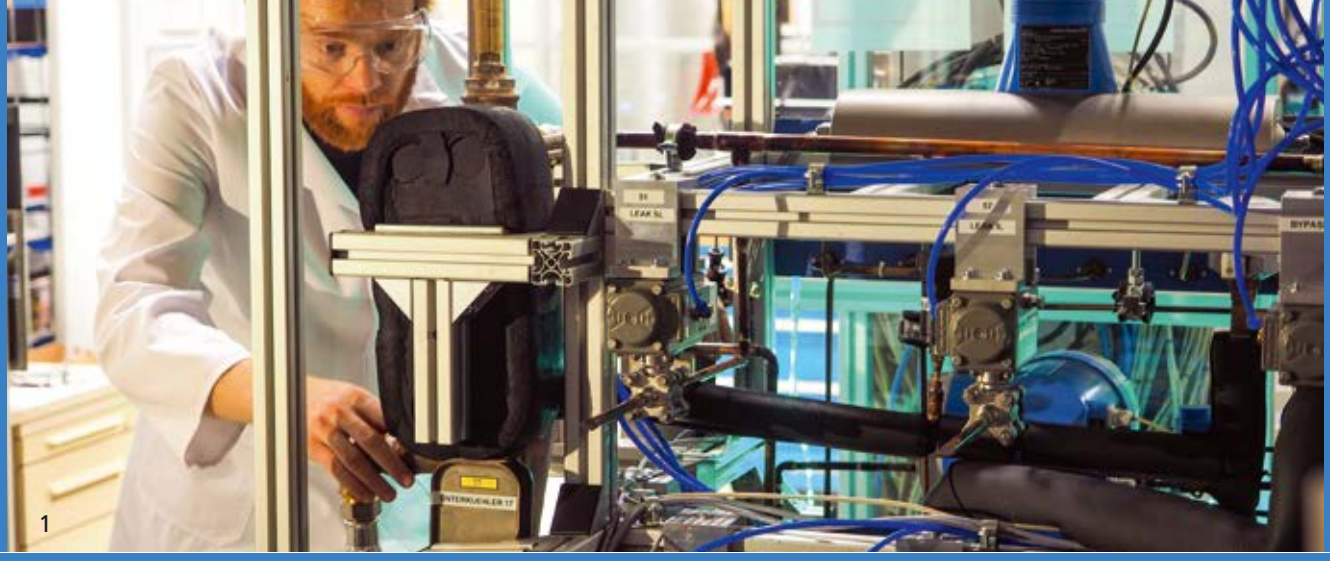
Storage tanks, systems
Konstantin Geimer
Phone +49 761 4588-5406

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 *Production line for pressurized hot water tanks.*
2 *Solar thermal array to provide energy for a local district heating network.*



Measurement and Testing of Heat Pumps

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TestLab
Heat Pumps
and Chillers

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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 makes it feasible to test different types of technology and system configurations over a broad spectrum of operating conditions with different heat transfer media (air, water, brine). In addition to 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 the set-up and the measuring of components and systems with flammable refrigerants or ammonia.

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 current (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 range 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, laser Doppler anemometry, shadowgraphy, gas chromatography, scanning vibrometry).

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

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TestLab
Power Electronics

The accredited TestLab Power Electronics offers the testing of electric units and systems in the high power range up to 10 megawatts. In doing so, it can draw on the extensive equipment of the Center for Power Electronics and Sustainable Grids in the new premises in Zinkmattenstrasse, Freiburg (page 74).

The equipment in the new laboratory enables us to test the electric properties of inverter systems, characterize them according to current grid connection guidelines and carry out climatic-chamber tests to clients' specifications. We mainly test PV and battery inverters, but also combustion engines such as combined heat and power (CHP) plants or loads such as charging stations for electromobility. At the new premises, different transformers connect test objects as well as test equipment to check their dynamic behavior in the grid (UVRT and OVRT). In addition, we can use a resonant circuit test rig to investigate the behavior of generators with a power rating of up to 400 kVA during unwanted formation of island grids.

Furthermore, 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 can be tested with our 4.5 MVA LVRT test container, directly on site. Furthermore, a flexibly configurable PV generator with a rated power of 1 MWp is available at our outdoor test field.

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

1 *View of the TestLab Power Electronics in its new premises in Freiburg.*

Roland Singer
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Standards and Specifications

- Accreditation according to DIN EN ISO / IEC 17025
- FGW TG3: Determination of the electrical characteristics of power generating units and systems in the medium-voltage, high-voltage and highest-voltage grid
- DIN VDE V 0124-100: Test requirements for generating units for the connection to and operation within the low-voltage grid
- DIN EN 61400-21: Measurement and assessment of power quality characteristics of grid-connected wind turbines
- FGW TG4: Demands on modelling and validating simulation models of the electrical characteristics of power generating units and systems
- 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 TG3 (Rev. 24)

R&D INFRASTRUCTURE

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area exceeding 16 700 m^2 and extremely modern equipment and facilities are the basis for our competence in research and development. These currently comprise more than 16 000 m^2 laboratory areas and workshops meeting different types of standards and certified clean-room laboratories with a floor area of 634 m^2.

The R&D infrastructure of Fraunhofer ISE is divided into seven laboratory centers and four production-relevant technological evaluation centers:

- 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
- Center for Power Electronics and Sustainable Grids
- Center for High Efficiency Solar Cells
- Center for Optics and Surface Science
- Center for Heating and Cooling Technologies
- Center for Material Characterization and Durability Analysis
- Center for Energy Storage Technologies and Systems
- Center for Fuel Cells, Electrolysis and Synthetic Fuels

The technical infrastructure is continually 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. For example, PV-TEC – Photovoltaic Technology Evaluation Center – was thoroughly modernized in 2018.

In 2019, Fraunhofer ISE extended the Center for Power Electronics and Sustainable Grids with new premises in the Zinkmattenstrasse in Freiburg. We are now equipped with internationally unique infrastructure, including our own connection to the 110 kV high-voltage grid. A transformer with 110 kV / 20 kV / 40 MVA and the associated switching units and cables from the backbone of our infrastructure to develop and test solutions for reliable and safe operation of grids based on power electronics. The Center for Power Electronics and Sustainable Grids in Freiburg consists of three laboratories in the Zinkmattenstrasse (Multi-Megawatt Lab, Medium-Voltage Lab, Power Converters Lab) and a further laboratory in the Heidenhofstrasse (Smart Energy Lab). The Smart Energy Lab is currently being modernized to create the DigitalGrid Lab, so that Fraunhofer ISE can bring its activities on analyzing and testing intelligent grids, digitalization and intelligent operation management together under a single roof.

Photo: Medium-voltage switching facility for connection to the test-field transformers and testing facilities in the Center for Power Electronics and Sustainable Grids.

CENTER FOR POWER ELECTRONICS AND SUSTAINABLE GRIDS

1

MULTI-MEGAWATT LAB

With our activities in the Multi-Megawatt Lab, we are working on solutions to develop modern inverters to become guarantors for safe and stable grid operation. Due to the extensive electric infrastructure and our highly accurate measurement technology, which extends up to the 110 kV level, we are able to test individual solutions, inverter systems and micro-grids in a realistic environment and investigate the effects on the electricity grid up to the multi-megawatt range. The accessible connection power of up to app. 10 MW is a special advantage for testing also of larger PV and battery inverters. Our test beds are equipped with special testing facilities such as a large climatic chamber, a highly dynamic 1 MVA grid simulator and a Fault Ride Through test rig for short-term undervoltages or overvoltages (UVRT / OVRT). This enables both the characterization of the dynamic properties of inverters connected to the grid and the investigation of reliability and lifetime.

Technical Facilities (1): *Test fields up to 6.4 MVA and from 260 V to 1120 V | Highly accurate, broadband performance measurement at the low-voltage, medium-voltage and high-voltage levels | PV simulators (2000 V / 1.4 MW) | Bidirectional DC source / battery simulator (1500 V / 1 MW) / High-dynamic grid simulator (up to 1000 V / 1 MVA) / Power Hardware in the Loop system (1 MVA / 20 kHz) | Stationary UVRT and OVRT test unit (10 MVA) | Mobile UVRT test container (4.5 MVA) | Switchable inductive and capacitive loads (7 MVAr) | Anti-islanding test stand (400 kVA) | Climatic chambers for large equipment (-30 °C to +80 °C, adjustable air humidity) | High-accuracy power measurement instruments (1000 V / 5000 A)*

MEDIUM VOLTAGE LAB

In the halls of the medium-voltage laboratory, inverter systems of up to 20 MVA can be connected to the 20 kV grid and tested and measured with the testing facilities of the laboratory. The tests of the medium-voltage inverter systems are operated from a separate control room in order to avoid any risk to the testing staff if the test object should be faulty. The testing hall of the medium-voltage laboratory can accommodate containers of up to 40 feet. Alternatively, larger systems can also be installed on the outdoor area. Furthermore, another hall with five independent cage cubicles is available. In the cages, e.g. power stacks of medium-voltage inverters or, more generally, circuits exceeding low-voltage limits are developed and taken into operation. Components, particularly semiconductor power components of silicon or silicon carbide with reverse voltages of 3.3 kV to 15 kV, are also measured in the cages. Various DC sources, transformers and load resistances are available for development and preliminary investigations.

Technical Facilities (2): *Test field with medium-voltage connection (20 kV / 20 MVA) | Medium-voltage DC source (10–40 kV / 3 × 220 kW) | Medium-voltage resistor (20 kVΔ / 20 kVY / 1 MW) | Medium-voltage transformer with several undervoltages (Dyn5, 20 kV / 3–6–10–15–20–30 kV / 2.5 MVA) | Medium-voltage variable transformer (Yyn0, 400 V / 3–12 kV / 100 kVA) | Railway transformer (16.7 Hz / 15 kV / 200 kVA) for connection to a highly dynamic grid simulator | Semiconductor test stands to characterize leakage currents in nA range at max. 30 kV | Avalanche effects (up to 4 kV / 100 A) and switching losses (up to 20 kV / 1000 A) | All set-ups suited for highly dynamic SiC semiconductors*


2


3


4

POWER CONVERTERS LAB

Also our research activities in the low and medium power range for a system voltage of up to 1500 V and power of up to 400 kW are located at the new premises in Freiburg. The focus is on research, development and testing of innovative power-electronic systems. New semiconductor technologies based on silicon carbide (SiC) or gallium nitride (GaN) allow us to implement promising hardware designs. Coupled with the corresponding cooling systems and hardware-relevant control technology, we develop power-electronic prototypes up to pilot-series devices. In all of our developments, above all efficiency and total system costs are in the foreground, in addition to the power density and power-to-weight ratio. We apply our knowledge of many years in diverse applications, such as photovoltaics, energy storage, charging infrastructure for electromobility and the aviation and space sector.

Technical Facilities (3): *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 measurement systems and accurate power measurement instruments | Measurement equipment for EMC disturbance (up to 200 A_{AC}/400 A_{DC}) | High-resolution, high-frequency thermography camera (videos) | Accurate inductivity measurement instrument and impedance analyser | Multi-gate vector grid analyser | Hardware-in-the-loop (HIL) system from OPAL-RT | Vapor-phase reflow soldering system*

SMART ENERGY LAB TO BECOME DIGITAL GRID LAB

The digitalization of the electricity grid and the grid integration of distributed energy systems are at the focus of research activities in our Smart Energy Lab. In order to investigate distributed energy supply systems in an even more realistic context, we are extending our current laboratory to become the Digital Grid Lab in future. Grid integration is simulated there by a hardware-in-the-loop grid simulator, which allows the virtual modelling of the electricity grid and automation technology. Complex grid sectors and operating situations can be modelled flexibly on a laboratory scale, and the interaction of systems in the grid can be tested. The test environment can reproduce the stationary and dynamic operating behavior in the power range of a typical low-voltage grid or micro-grid. We are focussing on grid operation and its automation and digitalization as well as integration into the energy market. In particular, we are paying more attention to grid coupling of the infrastructure for electromobility, the aspects of system technology and operation management of micro-grids and the automation of grid and system operation.

Technical Facilities (4): *Simulator for electrical load and generation | PV simulator with dynamic IV characteristics and time series of the solar input | HIL system to model generators, loads and storage units (CPC, batteries, heat pumps, electric vehicles) | Test stand for grid-connected energy management systems and smart metering | Grid-connected charging stations for electric vehicles | HIL system to reproduce the distribution grid with physical inputs and outputs to integrate hardware | Grid imitation system for testing*

TECHNOLOGICAL EVALUATION CENTERS

SiM-TEC – Silicon Materials Technology Evaluation Center
Dr. Stephan Riepe | Phone +49 761 4588-5636

At SiM-TEC, new technologies to produce silicon wafers for photovoltaics are developed and the materials used are evaluated. We work on all technological steps for the production of multi- and quasimonocrystalline wafers. 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 also develop the epitaxy of extremely pure silicon material by chemical vapor deposition (CVD) in a continuous process. For electrochemical processing of silicon wafers, we are equipped with an in-line etching facility which can carry out different whole-surface (156 mm × 156 mm) etching processes in electrically separate baths. We accompany all of the listed technological steps with numerous analytical options and simulation.

http://s.fhg.de/zqJ

PV-TEC – Photovoltaic Technology Evaluation Center
Dr. Ralf Preu | Phone +49 761 4588-5260

In PV-TEC, extremely modern 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. To this purpose, we develop and evaluate production processes and processing technology components, produce advanced industrial solar cell structures, characterize and develop materials and solar cells, offer further education and training for PV technology and transfer processes to our clients' premises, complete with on-site support. 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).

http://s.fhg.de/b7V

Module-TEC – Module Technology Evaluation Center
Stephan Hoffmann | Phone +49 761 4588-2235

Module-TEC offers extensive opportunities to develop module technologies. We focus on connection technology for crystalline solar cells, module integration of high-efficiency solar cells and the analysis and optimization of module efficiency. We also develop application-specific PV-modules e.g. for integration into buildings or vehicles. With our industrial production equipment and multi-facetted analytical platforms, we develop connection and encapsulation technology 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. In addition to the usual five ribbons per cell, we also process multi-wire technology, structured connectors or conductive back-sheets films as cell connectors for interconnection of full and half cells. Alternatively, we can produce module strings in a shingled configuration. In addition to soldering, solar cells can be connected by electrically conductive adhesives (ECA), which are applied in a fully automated, low temperature process. Modules in glass-backsheet or glass-glass configurations are encapsulated in our laminators in flat or curved forms.

http://s.fhg.de/CC9

Con-TEC – Concentrator Technology Evaluation Center
Maike Wiesenfarth | Phone +49 761 4588-5470

In Con-TEC, we use our industrial-relevant fabrication processes to produce concentrator modules with the highest efficiency and demonstrate ways to reduce costs. We manufacture prototypes in small series to evaluate new components, designs and processes. Our abilities and experience in selecting and processing optical silicones are unique; we use there silicones to produce optical components, for optical coupling of secondary optics or to encapsulate solar cells. A further research focus is on investigating the reliability of components. In concentrating photovoltaics, particularly the thermal connection 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 and components.

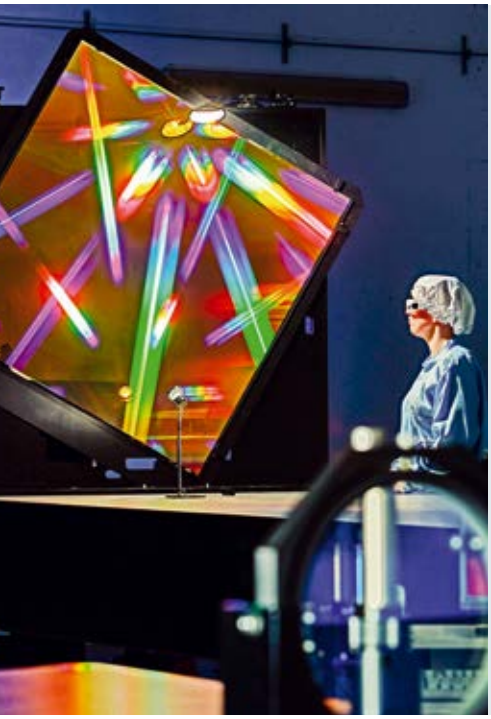
http://s.fhg.de/W7G

RESEARCH AND DEVELOPMENT CENTERS

Center for High Efficiency Solar Cells
Dr. Martin Hermle | Phone +49 761 4588-5265
Dr. Frank Dimroth | Phone +49 761 4588-5285

We develop technology with which highest PV efficiencies can be achieved, and implement it at an internationally leading level. Application areas for highest 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 solar cell sector, such as the records for bifacially contacted silicon solar cells (26,0 %) and multicrystalline silicon (22.3 %). We also hold several efficiency records for multi-junction solar cells, such as that for monolithic III-V on Si solar cells (34.1 %) and also that for the best four-junction solar cell under concentrated light (46.1 %). To advance this leading position still further, we will officially open a new laboratory building in 2020, which will contain clean-room laboratories with equipment suitable for meeting future technological challenges. Here, advanced PV technology can be tested and optimized in extremely modern laboratories with a floor area exceeding 1000 m^2.

http://s.fhg.de/bHJ



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

We develop optically functional surfaces for numerous applications, applying large-area coating and structuring processes. Within the coating technology, we work on solutions based on sputtering for thermal use of solar energy, photovoltaics, energy efficiency, thin-film batteries and hydrogen technology. Structuring surfaces on a micrometer to nanometer scale the achievement of a great variety of optical and non-optical functionalities. The large-area production of such customized surface structures is the basis for industrial implementation. For concentrating photovoltaics and solar thermal power plants we develop and assess optical components. We evaluate the concentrators, analyze soiling and develop cleaning methods.

http://s.fhg.de/sCK

Center for Heating and Cooling Technologies
Dr. Peter Schossig | Phone +49 761 4588-5130

We test and characterize many types of equipment and components for use in building technical services. 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 refrigerant circuits. Beyond this, we cooperate with our partners to develop individual measurement procedures which make the development and optimization process of equipment and more complex systems rapid and cost-effective, applying realistic, dynamic testing sequences, including hardware in the loop. We also use simulation tools to model and dimension heat exchangers, cooling circuits and systems.

http://s.fhg.de/nHm

Center for Material Characterization and Durability Analysis
Dr. Karl-Anders Weiß | Phone +49 761 4588-5474
PV modules: Daniel Philipp | Phone +49 761 4588-5414
PV cells: Dr. Martin Schubert | Phone +49 761 4588-5660

We have broad technical competence on testing and measuring many diverse materials for the active and passive use of solar energy, energy storage and building energy technology. We have special expertise in comprehensively investigating the properties of semiconductors, solar cells, photovoltaic modules, thermochemical and porous materials, phase change materials, heat-transfer fluids, polymers and coatings on glass and metals. We develop new methods to characterize materials, especially non-destructive analytical procedures, and to calculate material behavior and degradation. We investigate materials in different climatic zones under operational conditions. To estimate the performance and service life of materials, we use data from analytical measurements, real operation and accelerated aging tests.

http://s.fhg.de/yWz

Center for Energy Storage Technologies and Systems
Dr. Matthias Vetter | Phone +49 761 4588-5600
Dr. Daniel Biro | Phone +49 761 4588-5246

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 the field, to system monitoring. In the thermal storage field, this encompasses storage units both for heat and for cooling energy. We particularly concentrate 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 system 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 develop optimized charging and operating control strategies as well as battery system prototypes for a wide range of applications. Our activities also include modelling and simulation of batteries.

https://s.fhg.de/KTv

Center for Fuel Cells, Electrolysis and Synthetic Fuels
Prof. 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. To this purpose, we are equipped with excellent technical infrastructure.

https://s.fhg.de/ZWa

EDITORIAL NOTES

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EVENTS IN 2020

WITH PARTICIPATION OF FRAUNHOFER ISE

Zukünftige Stromnetze
Berlin, Germany,
29.–30.01.2020

E-World
Essen, Germany,
11.–13.02.2020

SiliconFOREST
Falkau, Germany,
01.–04.03.2020

Energy Storage Europe
Düsseldorf, Germany,
10.–12.03.2020

IRES 2020
Düsseldorf, Germany,
10.–12.03.2020

DKT Deutsche Kristallzüchtungstagung
Munich, Germany,
11.–13.03.2020

Porous Semiconductors Science and Technology (PSST)
Lido di Camaiore, Italy,
15.–20.03.2020

Symposium Photovoltaische Solarenergie
Kloster Banz, Bad Staffelstein, Germany,
17.–19.03.2020

LOPEC
Munich, Germany,
24.–26.03.2020

International Battery Seminar
Orlando, Florida, USA,
30.03.–02.04.2020

HFC + f-cell
Vancouver, Canada,
01.–02.04.2020

Urban Future Global Conference
Lisbon, Portugal,
01.–03.04.2020

11th International Workshop on Crystalline Silicon for Solar Cells and 4th Silicon Materials Workshop
Lisbon, Portugal,
20.–22.04.2020

Hannover Messe
Hanover, Germany,
20.–24.04.2020

OWPT Conference
Pacifico Yokohama, Japan,
21.–23.04.2020

Battery Show Europe
Stuttgart, Germany,
28.–30.04.2020

CPV 16 – International Conference on Concentrator Photovoltaic Systems
Denver, Colorado, USA,
04.–06.05.2020

PCIM
Nuremberg, Germany,
04.–07.05.2020

IFAT
Munich, Germany,
04.–08.05.2020

Heat Pump Conference
Jeju, South Korea,
11.–14.05.2020

Symposium Thermische Solarenergie
Kloster Banz, Bad Staffelstein, Germany,
12.–14.05.2020

14th SNEC PV POWER EXPO
Shanghai, China,
25.–27.05.2020

EMRS Spring Meeting
Strasbourg, France,
25.–29.05.2020

Silicon PV
Hangzhou, China,
01.–05.06.2020

EVS 33
Portland, Oregon, USA,
14.–17.06.2020

47th IEEE Photovoltaic Specialists Conference
Calgary, Canada,
14.–19.06.2020

ICMOVPE
Stuttgart, Germany,
14.–19.06.2020

Power Electronics Seminar
Munich, Germany,
15.–16.06.2020

Intersolar Europe
Munich, Germany,
17.–19.06.2020

IAEE International Conference 2020
Paris, France,
21.–24.06.2020

39th International Energy Workshop
Freiburg, Germany,
29.06.–01.07.2020

WHEC
Istanbul, Turkey,
05.–09.07.2020

ISHPC
Berlin, Germany,
23.–26.08.2020

CIRED
Paris, France,
24.–28.08.2020

EU PVSEC
Lisbon, Portugal,
07.–11.09.2020

EPE-ECCE European Conference on Power Electronics and Applications
Lyon, France,
07.–11.09.2020

ECSCRM European Conference on Silicon Carbide and Related Materials
Tours, France,
13.–17.09.2020

IAA Nutzfahrzeuge
Hanover, Germany,
24.–30.09.2020

f-cell 2020
Stuttgart, Germany,
29.–30.09.2020

Battery Experts Forum
Frankfurt, Germany,
29.09.–01.10.2020

26th Solar Paces
Albuquerque, New Mexico, USA,
29.09–02.10.2020

Chillventa
Nuremberg, Germany,
13.–15.10.2020

Electronica
Munich, Germany,
10.–13.11.2020