Fraunhofer

ISE

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

# Annual Report 2020/21

40 YEARS
FRAUNHOFER ISE
*#CreatingTheEnergyFuture*

The energy from the sun is a prerequisite for life on earth. We can utilize it in the form of heat, electrical or chemical energy. For four decades, the Fraunhofer Institute for Solar Energy Systems ISE, as Europe's largest solar research institute, has been conducting research on solar energy utilization for a fossil-free energy supply. Fraunhofer ISE develops a wide range of technologies and system solutions for the sustainable supply, distribution, storage and efficient use of renewable energy with the vision of supplying mankind with a cost-effective energy system based on renewables.

# Annual Report 2020/21

40 YEARS
FRAUNHOFER ISE
#CreatingTheEnergyFuture

# Foreword

With this annual report, we review a period that was dominated for all of us by the impact of the coronavirus pandemic. Despite the necessity to adapt all our ways of working, we can report that the pandemic has not caused any major damage to Fraunhofer ISE. Most projects could continue successfully under the adapted working conditions at the Institute. Despite the coronavirus crisis, the topics of climate change and energy transformation have not lost their urgency. In the following annual report, we present some aspects of our current work. More detailed information can be found on the homepage of Fraunhofer ISE.

In February 2020, we published a pivotal study entitled "Paths to a Climate-Neutral Energy System – The German Energy Transition in its Social Context". In this study, we linked transition paths for the energy transformation with social behavior for the first time. In autumn 2020, the scenarios that it sketches were recalculated to take the expected more ambitious goals of the European Green Deal into account, namely a reduction of greenhouse gases in the EU by 55 % in 2030 and 100 % by 2050. The results of the study support the scientific discourse to further develop the energy transformation.

The broadly based expertise of Fraunhofer ISE again led to invitations to participate in high-level advisory bodies. For example, Prof. Hans-Martin Henning was appointed in August 2020 by the German Federal Cabinet to the new "Independent Council of Experts on Climate Change", of which he is the Chairman. This independent expert body of five scientists advises the Federal Government on the implementation of the Federal Climate Change Act. Our study mentioned above also clearly identifies that green hydrogen will be a core element of the future energy system. It can make an essential contribution toward the goal of greenhouse gas neutrality in all sectors by 2050 and support the system integration of fluctuating energy supplies from renewable sources. In preparation of the National Hydrogen Strategy announced by the German Federal Government, the Fraunhofer-Gesellschaft developed a hydrogen roadmap and provided it to the Ministries that were involved in defining the strategy. The activity was led by the Fraunhofer Institute for Systems and Innovation Research ISI and Fraunhofer ISE. The hydrogen competence of the Institute and the Fraunhofer-Gesellschaft is also recognized in the European context: In July 2020, Prof. Christopher Hebling was nominated as an expert to represent Germany in the Executive Committee of the "Technology Collaboration Program for Research and Development on the Production and Utilization of Hydrogen" of the International Energy Agency IEA. In December, the German Hydrogen and Fuel Cell Association elected him to the reoriented Executive Committee and appointed him as its Vice President.

In addition, he was appointed by the German Minister for Economic Affairs and Energy, Peter Altmaier, to be one of the twelve members of the expert committee on "Future Funds for the Car Industry" that advises the Federal Government.

Another key technology for the energy transformation – also at the European level – is the heat pump, for which Fraunhofer ISE conducts research along the entire value chain. Dr. Marek Miara, the Business Developer for Heat Pumps at Fraunhofer ISE, was recently elected to the Executive Committee of the European Heat Pump Association.

An essential result of our studies on the energy transformation is also that the expansion of photovoltaics must be accelerated and become more vigorous. Eu-

ropean technological sovereignty should also be taken into account in this context. Prof. Andreas Bett is heavily involved in this initiative, which includes preparation of the white paper entitled "Sustainable PV Manufacturing in Europe – An Initiative for a 10GW GreenFab". Initial success is already visible, with several companies manufacturing solar cells in Europe again. Fraunhofer ISE is also a member of the European Solar Manufacturing Council (ESMC), which was recently founded to support European production.

The development of highest-efficiency solar cells has been a hallmark of Fraunhofer ISE for years. In order to ensure that this continues in the future, we completed the construction and initial equipment of our new laboratory building, the "Center for High Efficiency Solar Cells" (page 83) and have begun to occupy it. The building was financed with funding from the German Federal Ministry for Education and Research (BMBF) and the State of Baden-Württemberg, for which we are deeply grateful. In the new building, the development of tandem photovoltaic technology will be strengthened. This technology allows the present theoretical efficiency limit for silicon solar cells to be overcome, such that an even higher electricity yield per area can be achieved.

The energy-charts.info platform of Fraunhofer ISE was relaunched in September. New data and linking options were added to the interactive web page, its layout was completely redesigned and optimized for access via mobile devices.

Furthermore, two new Fraunhofer ISE spin-offs were founded. Software based on artificial intelligence for planning energy systems is the product offered by greenventory, a spin-off co-founded by KIT and Fraunhofer ISE. Our most recent spin-off, HighLine Technology GmbH, focuses on resource-conserving and efficiency-raising production technology for solar cells with the potential for cost reduction.

We are very pleased that Saskia Vormfelde accepted the position of Administrative Director at Fraunhofer ISE in June 2020. In this new function for the Institute, Ms. Vormfelde has initiated a process to advance the organization of the administrative units.

In 2021, we look forward to two special events: the official opening of the "Center for High Efficiency Solar Cells" mentioned above, and the festivities to celebrate the 40th anniversary of the Institute.

We extend our sincere gratitude to our project partners, Board of Trustees, auditors, scholarship donors, contact persons and funding sources in the Ministries at the Federal and State levels for support and funding of Fraunhofer ISE as well as good collaboration. Hoping that we all ride out the pandemic phase without greater injury, we look forward to continuing our cooperation in the future. At least as important as overcoming the pandemic is the urgent task of transforming our energy system as quickly as possible to become truly sustainable.

Prof. Hans-Martin Henning

Prof. Andreas Bett

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

# Table of Contents

40th anniversary

1282 employees

2 institute directors

88 % self-generated income

LARGEST SOLAR RESEARCH INSTITUTE IN EUROPE

104.8 million euros total budget 2020

119 doctoral students

77 lecture courses on universities

13 members on Board of Trustees

305 active patent families

46 scientists currently on university staffs

67 nationalities

158 new publications

2 new spin-offs in 2020

over 30 Memorandums of Understanding

1560 ongoing projects in 2020

# Fraunhofer ISE

In 2021, the Fraunhofer Institute for Solar Energy Systems, the largest solar research institute in Europe, will be celebrating its 40th anniversary. We have experienced many successes, large and small, milestones and technological breakthroughs during these four decades.

Today, more than 1200 people are employed at Fraunhofer ISE, conducting research on the major global topic of the energy transformation. With our scientific results, we contribute towards determining the direction the world of tomorrow will take for its energy supply. Our research and development activities address both the sustainable supply and distribution of energy as well as its storage and efficient utilization. Which business areas reflect this content and how the Institute is organized are demonstrated by the presented information, facts and figures.

Our declared goal is to help preserve our planet through our research and to ensure the basis of life for present and future generations. The fundamental prerequisite is to restructure the existing energy system worldwide in such a way that, in the future, fossil fuels will no longer be needed and humanity will be supplied reliably with inexpensive, renewable energy.

# Organizational Structure

The organizational structure of Fraunhofer ISE is defined, apart from administrative and staff units, by the two large scientific divisions, "Photovoltaics", and "Energy Technologies and Systems".

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

» Photovoltaics
» 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)

**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

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

**Dr. Harry Wirth**
Phone +49 761 4588-5858

### Heads of Energy Technologies and Systems Division

**Prof. Christopher Hebling**
Phone +49 761 4588-5195

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

**Prof. Christof Wittwer**
Phone +49 761 4588-5115

### Administrative Director

**Saskia Vormfelde**
Phone +49 761 4588-5336

### Communications

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

Top row, from left to right: Prof. Hans-Martin Henning, Prof. Andreas Bett, Saskia Vormfelde, Prof. Christopher Hebling; Middle row, from left to right: Karin Schneider, Prof. Stefan Glunz, Dr. Harry Wirth, Dr. Ralf Preu; Bottom row, from left to right: Prof. Christof Wittwer, Dr. Peter Schossig.

# 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.

# Profile

## Aim

The Fraunhofer Institute for Solar Energy Systems ISE, founded in 1981 in Freiburg, Germany, is the largest solar energy research institute in Europe. Currently, its 1200 staff members are committed to promoting an energy supply system that is based on renewable energy sources, sustainable, economic, safe and socially just. This goal is reflected in its research focusing on energy efficiency, sustainable energy supply, energy distribution and energy storage. As the transformation of the existing energy system is a global theme, our research activities extend over industrialized, threshold and developing countries. Parallel to basic funding from the Fraunhofer-Gesellschaft, around 88 % of the Institute's funding originates from contracts for applied research, development and high-technology services. The total budget of the Institute amounted to 104.8 million euros in 2020.

## Research approach

Our aspiration is to develop concretely implementable, technical solutions that we make available to our industrial partners, in order to work together with them on individual, customized solutions. This is in accordance with the Fraunhofer principle of applied research, and simultaneously makes an important contribution to securing the economic future and competitiveness of Germany and Europe. The success of applied research also demands interaction with politics and society that we are increasingly engaging during the early stages of our work.

Fraunhofer ISE consists of two large organizational divisions, "Photovoltaics" and "Energy Technologies and Systems" and addresses five market-oriented business areas (page 30 ff.). Our research approach ranges from materials research through component development to systems integration.

## Activities

The basis for the research and development activities of Fraunhofer ISE is modern R&D infrastructure at the highest technical level (page 74 ff.). This encompasses seven Laboratory Centers and production-relevant Technology Evaluation Centers with a total floor area of 17 800 $m^2$. The Institute also offers testing and certification services in its seven test and calibration laboratories that are accredited according to DIN EN ISO 9001:2015. On this basis, we can work as a reliable partner and implement R&D projects at the different levels of a technological life cycle as required by the individual contracts, demands and levels of maturity.

Our activities encompass:

- New material / process
- Prototype / pilot series
- Patent / license
- Software / application
- Analysis based on measurement technology / quality control
- Advice / planning / studies

1 Main building of Fraunhofer ISE in Freiburg.

# Sustainability

At Fraunhofer ISE, we are working on research and development for a sustainable global energy supply. In concrete terms, this means that not only the content of our research but also the accompanying processes needed in research and organization are guided by the principle of sustainable development.

With our research work, we contribute toward innovative solutions for the major challenges to society that the energy transformation and climate change raise. Our work directly addresses the goal of “Affordable and Clean Energy”, but also affects eight further Sustainable Development Goals (SDG) of the United Nations (see illustration).

For example, we work on solar-powered water purification and thus contribute to the goal of ensuring that the entire global population has access to clean water. Integrated PV projects, i.e. projects on integrating photovoltaic technology into buildings and vehicles or over agricultural land and bodies of water, promote sustainable land use by helping to solve land usage conflicts.

We develop environmentally friendly technology and systems-oriented innovations in these and many other fields to advance more sustainable economic management and a circular economy. However, sustainability is reflected not only by the content of our research: how the research processes themselves are conducted is also relevant.

One decisive mechanism to ensure that research results influence society is successful knowledge and technology transfer. As an applications-oriented research institution, we thus cooperate closely with partners from business and industry to develop marketable innovations for potential users. Further sectors that we deliberately involve


Graph: Relationships between the Sustainable Development Goals of the United Nations and the topics addressed by Fraunhofer ISE (highlighted).

e.g. by applying interdisciplinary and transdisciplinary research methods, include science and research, politics and society.

For a more sustainable development of our internal organizational processes, we also need an economically stable budget now and in the future, responsible cooperation, satisfied employees and environmentally benevolent material flows. As a technological institute, we rely on research processes that demand considerable investments of energy and resources, but we continually aim to reduce their ecological footprint.

Detailed information on our progress and the measures taken for a more sustainable development of the Institute can be found in our Sustainability Report for 2020.

# Cooperation

Scientific excellence depends on discourse between experts. Fraunhofer ISE is integrated into an excellent network at both the national and the international levels.

**External Branches**

In addition to its headquarters in Freiburg, Fraunhofer ISE has an external branch which is operated jointly with the Fraunhofer Institute for Microstructure of Materials and Systems IMWS in Halle – the Fraunhofer Center for Silicon Photovoltaics CSP, which focuses on crystallization technology and recycling technology.

At the international level, in South America, the Institute collaborates directly with the Fraunhofer Chile Research – Centro para Tecnologías en Energía Solar (FCR-CSET), Santiago, Chile, with solar generation of electricity, thermal solar energy, water purification and process heat as its main topics.

**Cooperation with Universities**

Fraunhofer ISE focuses strongly on educating future scientists. 46 employees teach at universities, and about 250 B.Sc., M.Sc. and Ph.D students work at the Institute, which cooperates directly with several universities in Germany and around the world.

Cooperation with the University of Freiburg is particularly close. In October 2015, the "Institut für Nachhaltige Technische Systeme" (INATECH Institute for Sustainable Technical Systems) was founded within the Technical Faculty and addresses sustainable materials, energy systems and resilience. INATECH is based on a close partnership between the University of Freiburg and the five Fraunhofer Institutes located in Freiburg. This makes INATECH unique in the research landscape and allows it to cover the complete spectrum, from fundamental research to industrial application. This cooperation is complemented by the "Sustainability Center Freiburg", which promotes networking with sustainability-oriented enterprises, associations and other actors from Freiburg, the surrounding region and beyond.

Fraunhofer ISE also participates actively in many other central institutions and activities of the University of Freiburg. For example, with our expertise in photovoltaics we were able to contribute to the acquisition of the important "livMatS Cluster of Excellence". For more than two decades, there has been close cooperation with the Freiburger Materialforschungszentrum FMF (Freiburg Materials Research Center), where our activities in organic photovoltaics are located. Similarly, we have a tradition of cooperating closely with the Faculties of Physics, of the Environment and Natural Resources, and of Chemistry.

Among the M.Sc. courses which Fraunhofer ISE has initiated in cooperation with the University of Freiburg are those on "Sustainable Systems Engineering", "Renewable Energy Engineering and Management" and "Solar Energy Engineering". Beyond Freiburg, Fraunhofer ISE cooperates with many other universities in Germany and abroad.

**Memoranda of Understanding**

In addition, the Institute maintains Memoranda of Understanding with more than 30 research institutes, enterprises and organizations around the world. The Institute is well connected at the national and the international levels within research and professional associations.

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.

# Cooperation Within the Fraunhofer-Gesellschaft

Systemic questions demand cooperation between partners covering a wide spectrum of competencies. Networking within the Fraunhofer-Gesellschaft strengthens this approach.

**Groups and Strategic Research Fields**
The Fraunhofer Institutes work together within competence-oriented groups. Together with 18 other institutes, Fraunhofer ISE worked within the Fraunhofer Group Materials, "Components MATERIALS" on innovations and innovation processes relating to materials. Since January 2021, Fraunhofer ISE has been a member of the newly founded Fraunhofer Group for Energy Technology and Climate Protection.

In addition, the Fraunhofer-Gesellschaft defines Strategic Research Fields so that it can react more specifically to research topics of the future and establish unique scientific-technological emphases. Fraunhofer ISE is represented in a leading role in two of the seven research fields: The Institute Director, Prof. Hans-Martin Henning and Prof. Welf-Guntram Drossel, Director of the Fraunhofer Institute for Machine Tools and Forming Technology IWU, are the Speakers for the "Resource Efficiency and Climate Technologies" research field. Prof. Christopher Hebling and Prof. Mario Ragwitz from the Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG are the Speakers responsible for the "Hydrogen Technologies" research field.

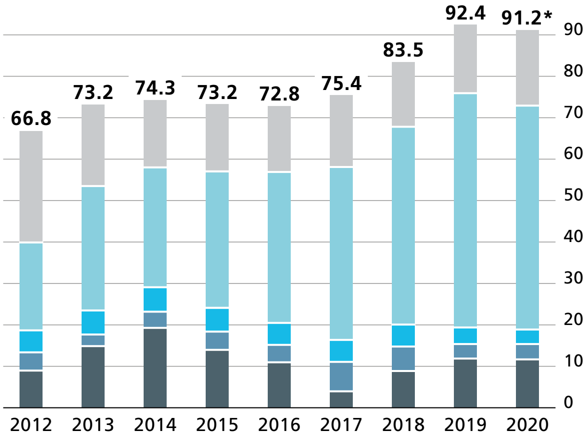
**Fraunhofer Alliances for Leading Markets**
Parallel to scientific excellence, excellent transfer of results is also a focus of applications-oriented research. In this context, the Fraunhofer-Gesellschaft has defined eight leading markets since 2020 that are primarily addressed by the Fraunhofer Alliances.

Fraunhofer ISE is not only one of 19 current members of the Fraunhofer Energy Alliance but has also been responsible for its management since its establishment in 2003. The Institute Director, Prof. Hans-Martin Henning, represents the goals of the Alliance to the outside world as its Speaker. Together with the Fraunhofer Battery and Water Systems Alliances, in which Fraunhofer ISE is also an active member, the Fraunhofer Energy Alliance organizes joint market access for its member Institutes and responds to the needs of the leading market of energy economics. As one of the largest energy research associations in Europe, the Alliance offers R&D services in the fields of Renewable Energy, Energy Storage, Energy Efficiency, Energy in the Digital Context, Energy Systems, Energy in the Urban Context, Energy Grids, and Climate and Environment.

Further networking within the Fraunhofer-Gesellschaft includes memberships in the Building Innovation and Space Alliances, as well as in the Fraunhofer Cluster of Excellence on Integrated Energy Systems (CINES), the Fraunhofer Networks for Intelligent Energy Grids, Sustainability and Hydrogen and the Fraunhofer Initiative "Morgenstadt – City of the Future".

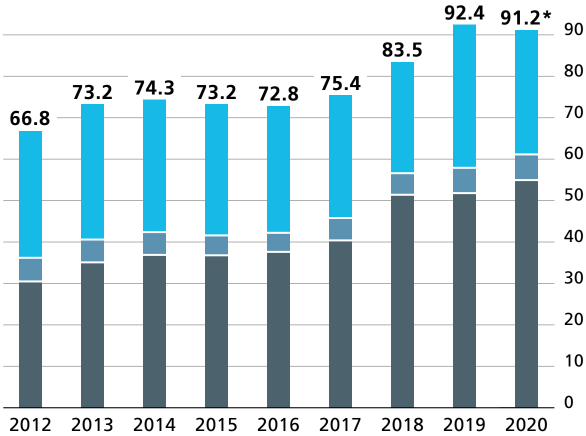
# The Institute in Figures

## Income in million euros**




■ Institutional funding / Fraunhofer special programs
■ Other ■ EU
■ State of BW/NRW (projects) / federal gov. ■ Industry

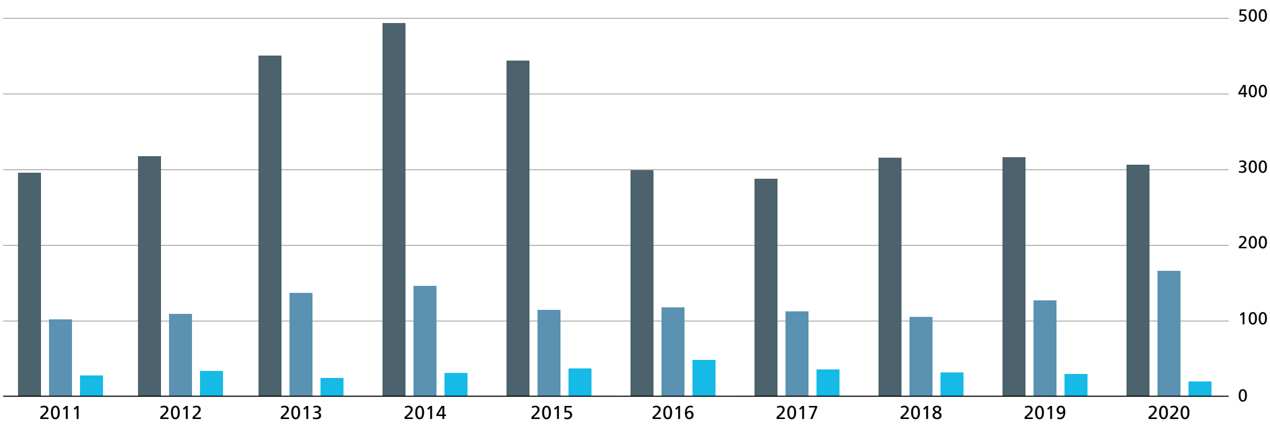
## Expenditure in million euros**




■ Staff employees ■ Others (diploma students, trainees, assistants, contract workers)
■ Materials expenditure

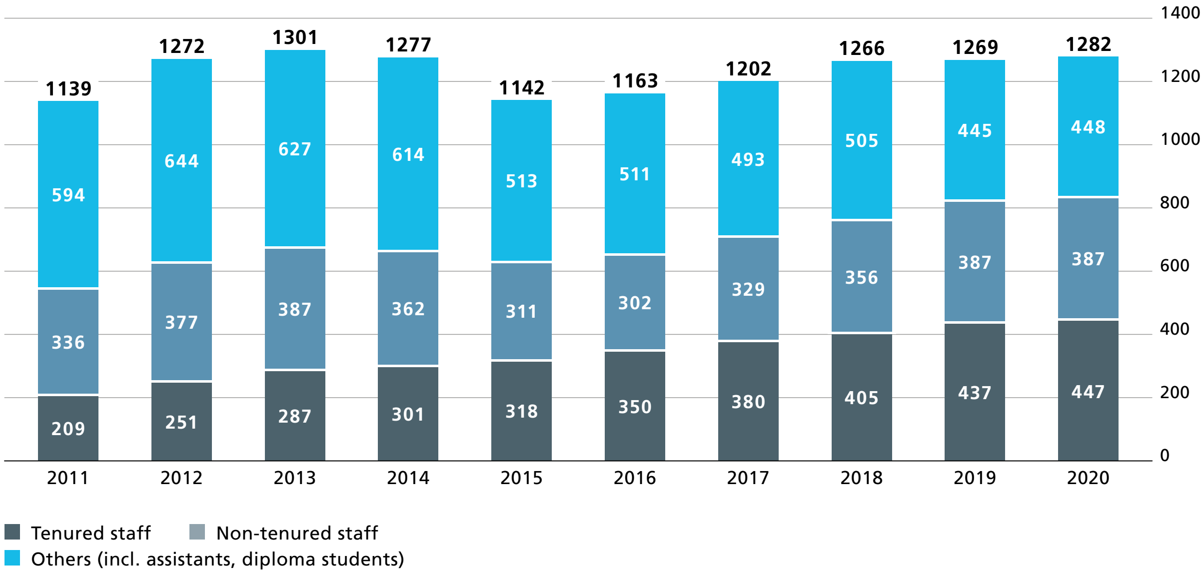
*preliminary **without investments – the total budget 2020 (incl. investments) totalled 104.8 million euros.

## Patents

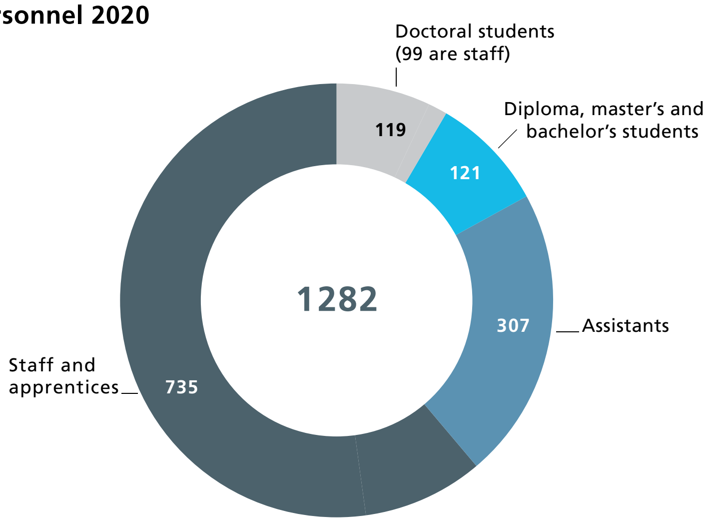



■ Active patent families on 31st December 2020
■ Active, granted patent families on 31st December 2020
■ Newly granted patents

## Personnel




## Personnel 2020




## Lecture Courses and Seminars

**67** University of Freiburg

**5** Offenburg University of Applied Studies

**2** KIT Karlsruhe Institute of Technology

**1** University of Koblenz-Landau

**1** TH Georg Agricola Bochum

**1** Ruhr University of Bochum

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

# Doctoral Theses

**Alexander Bett**
"Perovskite Silicon Tandem Solar Cells"
University of Freiburg, 2020

**Monika Bosilj**
"Hydrothermal Carbon Supports for Biorefinery-Related Catalysis"
University of Freiburg, 2020

**Rebekka Eberle**
"Influence of Realistic Operation Conditions on Silicon Solar Cells and Energy Yield"
University of Freiburg, 2020

**Markus Feifel**
"Hocheffiziente III-V-Mehrfachsolarzellen auf Silicium" (Highly Efficient III-V Multi-Junction Solar Cells on Silicon)
University of Constance, 2020

**Christoph Hank**
"Techno-Economic and Environmental Assessment of Power-to-Liquid Processes"
University of Freiburg, 2020

**Anna Heimsath**
"Optical Efficiency of Concentrating Solar Collectors – Investigation of Reflector Loss Mechanisms"
University of Bremen, 2020

**Ismail Kaaya**
"Photovoltaic Lifetime Forecast: Models for Long-Term Photovoltaic Degradation Prediction and Forecast"
University of Malaga, Spain, 2020

**Gayathri Mathiazhagan**
"Development of Future Stable Perovskite Solar Cells Through Interfacial Analysis Using Sub-Cells"
University of Freiburg, 2020

**Fabian Meyer**
"Transient Effects during Laser Processing of Silicon for Photovoltaic Applications"
University of Freiburg, 2020

**Katharina Morawietz**
"Experimentelle Analyse von horizontalen und leicht geneigten Zwei-Phasen-Thermosiphons für die solarthermische Fassadenintegration" (Experimental Analysis of Horizontal and Slightly Tilted Two-Phase Thermosyphons for Solar-Thermal Façade Integration)
Technical University of Darmstadt, 2020

**Hannah Neumann**
"Untersuchung eines Latentwärmespeichers für Prozesswärmeanwendungen" (Investigation of a Latent-Heat Storage Unit for Process-Heat Applications)
University of Freiburg, 2020


1

**Felix Predan**
"Development of Highly Efficient Four-Junction Solar Cells Based on Antimonides"
University of Freiburg, 2020

**Sönke Rogalla**
"Analyse frequenzabhängiger Netzwechselwirkungen von selbstgeführten Wechselrichtern mittels differentieller Impedanzspektroskopie und Oberschwingungsquellenbetrachtung" (Analysis of Frequency-Dependent Grid Interactions of Self-Commutated Inverters by Differential Impedance Spectroscopy and Observation of Upper-Harmonic Sources)
Technical University of Braunschweig, 2020

**Mohamed Kamal Ouda Salem**
"New Routes for Efficient and Sustainable Oxymethylene Ethers Synthesis"
Technical University of Munich, 2020

**Jörg Schube**
"Metallization of Silicon Solar Cells with Passivating Contacts"
University of Freiburg, 2020

**Patricia Schulze**
"High Band Gap Perovskite Absorbers in Monolithic Perovskite Silicon Tandem Solar Cells"
University of Freiburg, 2020

**Oliver Selinger-Lutz**
"A Robust and Cost-Efficient Smart Grid Concept Based on Ripple Control"
University of Freiburg, 2020

**Leonard Tutsch**
"Implementing Sputter-Deposited Transparent Conductive Metal Oxides into Passivating Contacts for Silicon Solar Cells"
University of Freiburg, 2020

**Rahel Volmer**
"Instationäre Verdampfung von Wasser aus Drahtgewebestrukturen bei subatmosphärischen Drücken" (Unsteady Evaporation of Water from Wire Mesh Structures at Sub-Atmospheric Pressures)
Technical University of Darmstadt, 2020

**Sven Wasmer**
"Sensitivity Analysis of Silicon PERC Solar Cells"
University of Freiburg, 2019

1 The successful completion of doctoral theses from Fraunhofer ISE was celebrated online in December, 2020.

# Prizes and Awards

**Dr. Sven Killinger, Dr. David Fischer**
"Make it Matter" Award
"Start-up greenventory"
Start-up competition of the Elektrizitätswerke Schönau
December 2019, Freiburg, Germany

**Simone Mastroianni**
Poster Prize of the Journal of the
Royal Society of Chemistry (RSC),
"Double Mesoscopic HTM-Free Perovskite Solar Cells: Overcoming Charge Transport Limitation by Sputtered 40 nm Al2O3 Isolating Layer"
IPEROP20, 20. – 22.01.2020, Tsukuba, Japan

**Cornelius Armbruster**
Gigawatt Winner
Article: "Batteriesteller des Fraunhofer ISE"
(Battery Charger from Fraunhofer ISE)
PV Magazine, Messe Düsseldorf and
Energy Storage Europe
March 2020

**Robin Lang**
Young Scientist Prize of the Deutschen Gesellschaft für Kristallwachstum und Kristallzüchtung (DGKK)
Conference paper: "MOVPE Growth of GaAs with Growth Rates up to 280 µm / h"
DKT2020, 11. – 13.03.2020, Munich, Germany

**Dr. Tilmann Kuhn**
Leon Gaster Award 2019
Conference paper: "Cross-Validation and Robustness of Daylight Glare Metrics" (co-author)
Society of Light and Lighting
21.05.2020, London, United Kingdom

**Markus Feifel**
Best Student Award
Conference presentation: "Advances in Epitaxial GaInP / GaAs / Si Triple Junction Solar Cells"
IEEE PVSC 47, 15.06. – 21.08.2020

**Sang Hyuk Lee**
Best Paper Award
Conference paper: "Learning from Tetris: A New Approach for the Automated Configuration of the Interconnection Layout of BIPV Modules for Large-Scale Application"
IEEE PVSC 47, 15.06. – 21.08.2020

**Dr. Felix Predan**
Best Student Award
Conference presentation: "Wafer-Bonded GaInP / GaAs / GaInAs / GaSb Four-Junction Solar Cells with 43.8 % Efficiency under Concentration"
IEEE PVSC 47, 15.06. – 21.08.2020

**Moritz Bitterling**
Alumni Prize 2020
M.Sc. thesis: "Messung des räumlich aufgelösten Reflexionsgrades von Strahlungsempfängern in Solarturmkraftwerken"
(Measurement of Spatially Resolved Reflectance of Radiation Receiver in Solar Power-Tower Plants)
Förderverein Alumni Freiburg e. V.
01.07.2020, Freiburg, Germany

**Dr. Andreas Büchler**
Südwestmetall Award 2020
Doctoral thesis: "Laser-Structured Plated Metal Contacts for Silicon Solar Cells"
Verband der Metall- und Elektroindustrie Baden-Württemberg e. V. (Südwestmetall)
July 2020

**Christoph Messmer**
Student Award
Conference presentation: "The Race for the Best Silicon Bottom Cell: Efficiency and Cost Evaluation of Perovskite-Silicon Tandem Cells"
37th EU PVSEC, 11.09.2020

**Dr. Patricia Schulze**
Student Award
Conference presentation: "High Band Gap Absorber for Monolithic Perovskite Silicon Tandem Solar Cells Reaching 25.1 % Certified Efficiency and Ways Beyond"
37th EU PVSEC, 11.09.2020

**Robert Meyer et al.**
Seifriz Prize – Special Prize for Students
Project: "SHK4FutureEnergysystems"
Verein Technologietransfer Handwerk e. V.
23.09.2020, Offenburg, Germany

**Mathias Drews, Manuel Bauer**
4th Place in the Deutschen Nachhaltigkeitspreis 'Forschung', (German Sustainability Prize 'Research')
"Funky Upcycling"
German Federal Ministry for Education and Research (BMBF)
28.09.2020

**Dr. Sönke Rogalla, Sebastian Kaiser, Prof. Bruno Burger, Bernd Engel**
Best Paper Award
Conference paper: "Determination of the Frequency Dependent Thévenin Equivalent on Inverters Using Differential Impedance Spectroscopy"
IEEE 2020, 28.09. – 01.10.2020

**Dr. Matthias Klingele, Dr. Roman Keding**
f-cell Award, 'Research & Development' category
Project: "Through-Plane Ionomer Gradients in Fuel Cell Catalyst Layers for Enhanced Power Density"
Peter Sauber Agentur
29.09.2020, Stuttgart, Germany

**Dr. Felix Predan**
Eva-Mayr-Stihl-Nachwuchsförderpreis 2020
Dissertation "Development of Highly Efficient Four-Junction Solar Cells Based on Antimonides"
University of Freiburg
04.11.2020, Freiburg, Germany

**Dr. Martin C. Schubert**
Best Paper Award
Conference paper: "The Potential of Cast Silicon"
SiliconPV 2020

**Rebekka Eberle**
Best Paper Award
Conference paper: "Breakdown of Temperature Sensitivity of Silicon Solar Cells by Simulation and Experiment"
SiliconPV 2020

**Dr. Matthias Vetter**
Global Excellence Award 2020, 'Renewable Sector' Category
Energy and Environment Foundation
Virtual 4th World Water Summit 2020 and Virtual 11th World Renewable Energy Technology Congress
15.12.2020, Delhi, India

1 The f-cell Award was presented by the State Minister for the Environment, Baden-Württemberg, Franz Untersteller (left), to Dr. Roman Keding (center) and Dr. Matthias Klingele (right).

# Interaction Between Science, Society and Politics

**Research institutes interact with politics in different ways. This includes preparing scientific studies and roadmaps that serve as a basis for decisions, offering informational events for political decision-makers or presenting scientifically based facts to the wider public, which in turn affect political decisions by opinion-shaping processes in society. Last but not least is the advice that politicians seek out directly. For instance, Prof. Hans-Martin Henning was recently appointed to the Independent Council of Experts on Climate Change, which advises the German Federal Government. In the following conversation, the two Institute Directors, Prof. Hans-Martin Henning and Prof. Andreas Bett, discuss these and other questions concerning the interaction between science, society and politics.**

### Science Provides Advice for Energy Policy

**Henning:** When we talk about political advice by our Institute, I find it important to start with our main task: Complying with our mission, we work predominantly on technological development topics, technical questions and approaches for a new energy system. Connecting the multitude of new technical components along the entire chain from supply through conversion and distribution up to end-use simultaneously implies diverse and complex systemic questions. In this area, we have also built up extensive know-how leading to high-performance techno-economic holistic models. This profound knowledge of technological and systemic topics is the basis for our contribution to political counselling, because political concepts for the energy transformation and its implementation need well-founded knowledge of the technical options and their implications. Thus, when we contribute to politics, when we speak to politicians, ministries and also associations, our most important contribution is knowledge that is underpinned by evidence. Even when we, as an Institute or as individuals, have an opinion on questions that go beyond our scientific work, we should contribute in our political advisory activity to fields where we are scientifically active and feel competent to join the discourse.

### Science Informs Society

**Bett:** I would extend the framework beyond direct political counselling and mention scientifically based sources of information that we provide to the general public and particularly to representatives of the media. Politics is also influenced by public opinion and this is based on information from the media. Thus, it is very important in my view to provide fact-based information to editorial teams. Examples from Fraunhofer ISE include the "Energy Charts", the "PV Report" or the "Facts on PV in Germany". A wide spectrum of information channels offers points of contact with the population and leads to greater understanding of the new technologies, which is an important precondition for their acceptance. This in turn finally influences political activity. For me, this interaction between technological elucidation, acceptance in society and political decisions is one of the most exciting aspects.

And then of course, there is also the point that one is concretely approached by individual politicians and at times enters borderline areas, because it is not always possible to help politics simply on the basis of technologically orientated argumentation. Then one also adopts arguments from other stakeholders, which may be less scientifically based than those from one's own areas of research. Caution is advisable in such cases.

**Henning:** In this context, it is interesting to observe that this play of forces with respect to the energy transformation, and thus also to the 40-year history of Fraunhofer ISE, has changed dramatically. When the Institute was founded, solar researchers were outsiders, whose voice was hardly heard. Then, a long, polarizing combat was fought against renewable energy, and today there is widespread consensus that an energy transformation without renewable energy cannot succeed. In this connection, it is also exciting to note the parallel development within the Fraunhofer-Gesellschaft: It is only now that the energy economic sector has been identified and named as one of the eight most important defining markets for the Fraunhofer-Gesellschaft.

**Knowledge Transfer in Collaboration**

**Henning:** I find it particularly rewarding that our work is becoming increasingly interdisciplinary, with cross-fertilization from colleagues in economics and political and social sciences, and that new perspectives and options for action arise from the dialogue. A good example is the study on sector integration that resulted from the ESYS project addressing energy systems of the future. Within this interdisciplinary work under the auspices of German scientific academies, I gained a much deeper understanding of $CO_2$ pricing and am now very convinced that a trans-sectoral price is a central control instrument, specifically in the context of sector integration.

**Agenda-setting for Research Politics**

**Bett:** Another aspect of the interaction with politics is the fact that we are also dependent on politics regarding to research politics and which research strategies are developed. We certainly exert our influence on decision processes affecting the design of technological roadmaps, together with our networks and clients.

Once again, a glance at our history: Fraunhofer ISE has always concentrated on high and highest efficiency in photovoltaics; this approach has meanwhile established itself in the market. Since its inception, Fraunhofer ISE has conducted research on hydrogen, power electronics, battery systems technology, energy-efficient buildings and the many associated systemic aspects. It was a great visionary achievement by the founder of the Institute, Prof. Adolf Goetzberger, already to take account of these topics, which are so important for the energy transformation, at a time when this concept was not yet commonplace. Due to this long-term experience over the breadth of energy-technical topics, our Institute has always been able to influence research politics to some extent. And there is yet a further aspect: Beyond agenda-setting purely in research politics, we can mention the example of photovoltaic manufacturing, where we campaign with conviction for starting up PV production in Europe again, based on our studies on economic feasibility. This is an effort to retain technological sovereignity and industrial production in Germany, which is also part of our Fraunhofer mission in the sense of industrially relevant applied research.

**Sustainability as a Fraunhofer Mission**

**Henning:** The vision of Fraunhofer ISE identifies the values that guide it, expressing the conviction of the Institute and its staff that we must conserve the resources of our planet and that, in particular, a sustainable energy system is needed to achieve this goal. This attitude is becoming increasingly accepted by the Fraunhofer-Gesellschaft, where we speak today of values-oriented value creation and the Sustainable Development Goals occupy a prominent position on the agenda. Our research thus contributes to a future that will enable the continued existence of humankind and the planet as we know it.

1 Institute Director, Prof. Hans-Martin Henning.

2 Institute Director, Prof. Andreas Bett.

# PV-TEC – production research for solar cells

AUTOMATED MEASUREMENT OF SOLAR THERMAL POWER PLANTS WITH "AVUS"

field measurements of 300 heat pumps

15.2 % efficiency record for organic solar cells with at least 1 $cm^2$ area

## Self-Sufficient Solar House

30 buildings with thermally activated building components analyzed

MICRO-ENCAPSULATED LATENT HEAT STORAGE MATERIALS FOR BUILDING COMPONENTS

34.5 % efficiency for tandem solar cells with III-V and silicon semiconductors

46 % efficiency record for four-junction solar cells under concentrated sunlight

WORLD'S FIRST PASSIVE HIGH-RISE BUILDING IN FREIBURG

SOLAR HYDROGEN FILLING STATION

25.1 % efficiency for monolithic perovskite-Si tandem solar cells

800 W heating power from ventilation device with heat pump

26 % efficiency record for bifacially contacted silicon solar cells

RAPPENECKER HÜTTE – FIRST PV-POWERED HIKERS' INN IN EUROPE

1000 V stationary lithium-ion battery storage unit

28 kWh lithium-ion battery system for electric vehicles

up to 350 kW conductive charging infrastructure

99.03 % efficiency for PV inverters

1000 hours remote operation of methanol synthesis plant based on purified flue gas

The Energy Charts give transparency to the energy transformation process

# Highlights of Our Research

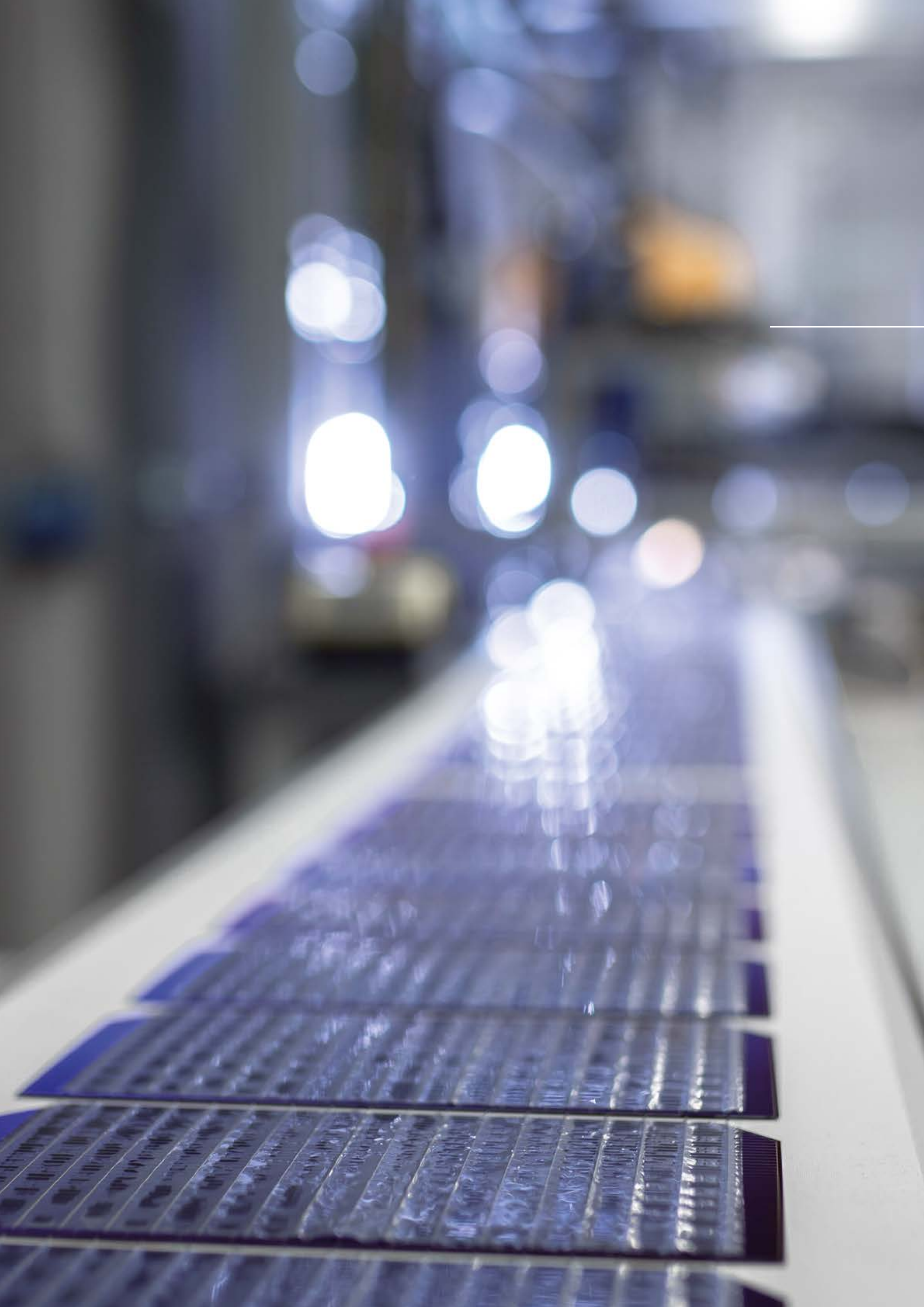
The Fraunhofer Institute for Solar Energy Systems ISE has been conducting research for 40 years for a sustainable energy supply. We cover different research areas both with projects that are very close to application and others that are oriented toward the future.

The two large organizational divisions, “Photovoltaics” and “Energy Technologies and Systems” address the following five, market-oriented business areas:

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

As a partner to industry, Fraunhofer ISE orientates itself toward its clients’ needs and thus makes an important contribution to their commercial success. Due to its many years of experience with many different customers, the Institute is well acquainted with the working methods and requirements of companies. Customized to individual demands and specific questions, we accompany our clients reliably from the first product idea up to commercial maturity.

This innovative spirit is reflected in our current key topics, “Tandem Photovoltaics” (pages 28/29) and “Heat Pumps” (pages 52/53). Further selected research results and projects are presented on the following pages.



# Photovoltaics

Photovoltaics is a central pillar of the energy supply of the future, as the most recent study by Fraunhofer ISE on the development of the German energy system confirms. For 40 years, Fraunhofer ISE has made an important contribution to increasing the efficiency of solar cells and the reliability of PV modules and power plants, as well as further developing sustainable and cost-effective production processes for cells and modules. It is a research partner for the European solar industry along the entire PV value chain. Today, solar electricity is the least expensive form of energy in many parts of the world, but the potential of the technology is far from being exhausted.

With a view to future technological challenges, we are pleased that we can expand our infrastructure with the Center for High Efficiency Solar Cells (page 83). Our thanks for the financing of this new building – with 1000 $m^2$ of the most modern laboratory areas and cleanroom equipment – go to the German Federal Ministry for Education and Research (BMBF) and the State of Baden-Württemberg. Alongside the further development of silicon and III-V multi-junction solar cells, a focus of the new center is on the promising approach of Si-based tandem photovoltaics. This is the combination of solar cell materials with different electronic properties such as III-V semiconductors, perovskites or silicon. Radiation from the broadband solar spectrum can thus be converted even more efficiently into electricity and the theoretical efficiency limit for conventional solar cells of only a single solar cell material can be overcome. This results in the potential to save solar cell and module materials and thus contributes to the sustainability of photovoltaics. In addition, the area needed for PV expansion is reduced by the application of high-efficiency tandem solar cells. This applies particularly for their application in integrated photovoltaics, i.e. the utilization of PV modules in areas that are already used or built over, such as building envelopes and vehicle bodies. Multiplying installed PV by a factor of ten, which Germany needs to meet its climate protection goals, demands efficient and sustainable technologies.

High-performance tandem cells place highest demands on series connection and encapsulation to produce durable and safe modules. We have adapted the industrial processing platforms in our Module-TEC to meet these demands. We have implemented different low-temperature connection technologies, which simultaneously eliminate most module-level power losses.

Resource-saving production technology is playing an increasingly important role alongside increases in efficiency. The spin-off, HighLine Technology GmbH, originated from the photovoltaic production technology area. The goal of the start-up is to commercialize a new process that was developed at our institute, in which the metal contacts on the front surface of the solar cell are applied by a contactless dispensing procedure. This saves resources, increases the electricity yield and reduces costs.

Beyond its technological development, Fraunhofer ISE is also active in reviving the European solar industry to retain the technological sovereignty of Europe. For example, the Institute is supporting the "Solar Europe Now" initiative, which demands recognition of solar energy as a key technology to achieve the goals of the European Green Deal.

Photo: Cell string interconnected with Smart Wire Connection Technology (SWCT™) at Module-TEC, Fraunhofer ISE.

# Tandem Photovoltaics – The Road to Higher Conversion Efficiencies

Photovoltaics is a central pillar for sustainable energy systems and therefore still needs to be applied much more widely. Solar cell efficiency plays a decisive role in further reducing the levellized cost of electricity. For this reason, tandem photovoltaics is becoming increasingly important as it allows the theoretical efficiency limit of the commercially dominant silicon solar cell to be overcome.

Tandem or multi-junction solar cells use two or more photovoltaic absorbers with different electronic band gaps. In a combination of different absorbers, the radiation in the broadband solar spectrum can be converted much more efficiently, so that more electricity is generated per unit area. Apart from higher efficiency, the tandem approach offers promising advantages, such as lower resource consumption and energy demand to produce the cells relative to their nominal power. In order to fully exploit this potential, intensive activities in research and development are needed. Indeed, we are meeting this challenge in 2021 with the opening of the "Center for High Efficiency Solar Cells", which includes more than 1000 $m^2$ of clean rooms with the most modern equipment. In order to achieve the highest efficiencies, detailed characterization of cells and materials is extremely important. In particular, accurate determination of the efficiency in our CalLab PV Cells and CalLab PV Modules, which we also offer externally as a service, is mandatory.

**Concentrator Applications**

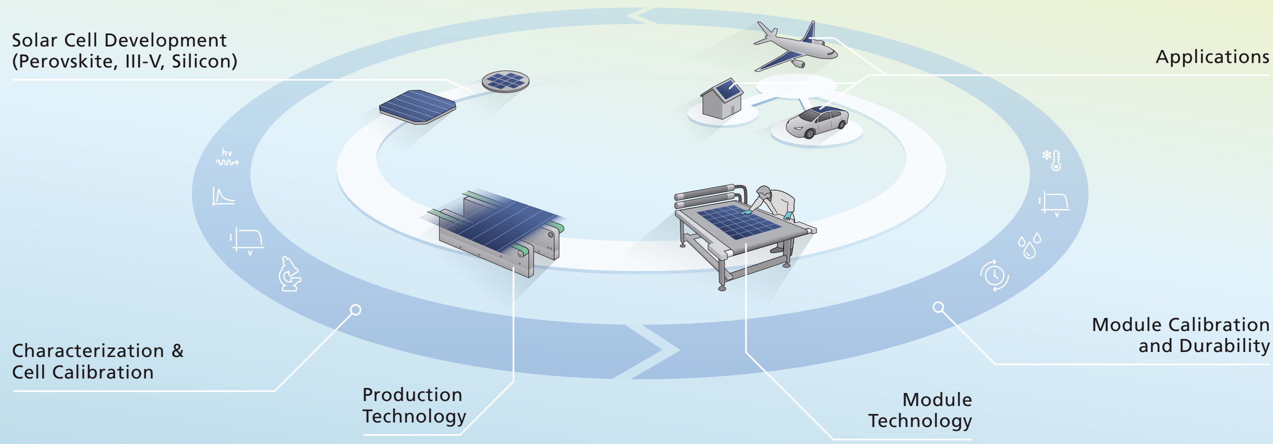
Competence in tandem photovoltaics at Fraunhofer ISE is based on long-term experience with monolithic concentrator tandem cells of III-V semiconductors, with peak efficiencies of up to 46.1 %. We are investigating new cell structures with the goal of achieving efficiencies exceeding 50 %. In 2020, we successfully developed a novel, wafer-bonded four-junction solar cell based on antimonides (GaInP / GaAs / GaInAs// GaSb) with a peak efficiency of 43.8 %. This creates an excellent foundation for our further work. Our research focuses on optimizing the III-V epitaxy, adapting the wafer-bonding process and developing a suitable processing route to produce the metal fingers and anti-reflective coatings.

**Applications with Low or No Concentration**

In the field of non-concentrating tandem PV, we work with III-V-silicon and perovskite-silicon tandem solar cells. We possess first-class technological facilities and excellent scientific expertise for all three groups of materials. In particular, our long-term experience in developing and producing silicon solar cells provides a solid basis for developing suitable silicon solar cells, which as the bottom cells strongly influence the efficiency and levellized cost of electricity for tandem solar cells. In addition to analyzing the technical feasibility, we also evaluate the economic viability by determining the levellized cost of electricity to be anticipated for different tandem approaches.

**III-V on Silicon**

The III-V / silicon material combination holds strong interest for the next generation of solar cells with the highest efficiency. Fraunhofer ISE is working on different approaches to produce combinations of III-V and silicon solar cells. In 2020, the world record for efficiency, which the Institute has held since 2019, was improved to 34.5 %. For the record cell (GaInP / AlGaAs // Si), the III-V semiconductor films, only a few micrometers thick, were transferred from a gallium arsenide substrate onto silicon, with the layers being connected by wafer bonding. As this technology is efficient but expensive, Fraunhofer ISE is also working on direct production processes and achieved a new world record efficiency of 25.9 % in 2020 for a III-V / Si tandem solar cell which was grown directly on silicon.




**Perovskite on Silicon**

Perovskite-silicon tandem solar cells promise lower levellized costs of electricity and lower resource consumption than conventional silicon solar cells. In laboratory experiments, the maximum efficiency has already exceeded that of silicon solar cells. The first companies are beginning to implement this technology industrially. Within the "PersiST" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE achieved a record efficiency of 25.1 % for a monolithic perovskite-silicon tandem solar cell. The perovskite absorber that we developed features an optimal band gap of 1.68 eV and high photostability. We are now developing this technology further within the Fraunhofer "MaNiTu" lighthouse project, in which not only high efficiencies but also the development of novel, lead-free perovskite are the main objectives. Assuming that a high efficiency of 28 % and a lifetime of at least 23 years can be achieved successfully, the first cost analyses identify great ecological added value.

**Production Technology**

Cost-effective solutions for production technology are decisive for the transfer of laboratory prototypes to the industrial context. At Fraunhofer ISE, innovative processes and equipment are continually evaluated and optimized regarding their suitability for tandem photovoltaics. Sustainability aspects such as saving energy and materials play a central role. In the Photovoltaic Technology Evaluation Center, we have extensive expertise in all relevant production technologies and long-term experience in the transfer to industrial production. We offer a wide range of technologies to deposit perovskite absorber layers. Wafers in industrial formats can already be blade-coated; spray coating and corresponding evaporation processes are currently under development.

**Module Technology**

In the Module Technology Evaluation Center at Fraunhofer ISE, we are investigating reliable solutions to connect and encapsulate perovskite-silicon and III-V-silicon tandem solar cells and analyze the reliability of these novel modules in our TestLab PV Modules according to current IEC standards.

Perovskite-silicon solar cells are particularly sensitive to moisture, temperature and mechanical loads. III-V tandem solar cells are thin and flexible. Thus, the classic processes from crystalline silicon solar cells for connection and encapsulation only hold limited relevance. We develop different connection procedures, such as shingling for III-V/Si tandem solar cells to make the PV modules more efficient. In this way, we can minimize the cell-to-module losses and make very high module efficiencies feasible. We develop different connection processes for perovskite-Si tandem solar cells, e.g. applying conductive adhesives, Smart Wire Connection Technology (SWCT) and low-temperature soldering. We can draw on long-term experience to meet the module demands on reliability, electric performance and low production costs. As the module mass plays a role for integration into different applications, we have developed encapsulants and processes for III-V/Si tandem solar cells with which we can achieve a module mass of 380 g/m$^2$, compared to the classic silicon module with about 10,000 g/m$^2$.

1 Tandem photovoltaics is among the fastest-developing solar technologies today.

## Silicon Photovoltaics

Excellent results have been achieved, for both a-Si/c-Si heterojunction solar cells and for the TOPCon technology that was developed at Fraunhofer ISE. By producing screen-printed contacts with finger widths of less than 20 µm for the first time, we have succeeded in demonstrating the sustainable potential for improving this technology. The development of a new, high-throughput facility for metallization represents another highlight in the context of growing demands on industrial production.

## III-V and Concentrator Photovoltaics

Tandem solar cells of III-V semiconductors achieve the highest efficiencies of all types of solar cells and are used for space and concentrator applications. However, in combination with silicon, this material also offers high potential for terrestrial photovoltaic modules without concentration. Here, we achieved an efficiency of 25.9 % for a III-V/Si tandem solar cell that was grown directly on silicon.

## Perovskite and Organic Photovoltaics

Perovskite solar cells already achieve very high efficiencies in the laboratory. Our goal here is to develop cell and module concepts that can be upscaled. In addition, perovskite absorbers are very well suited for tandem photovoltaics, which allowed us to reach a calibrated efficiency of 25.1 % for monolithic perovskite / Si tandem cells. For organic solar cells, we achieved a record certified efficiency for cell areas ≥ 1 $cm^2$ of 15.2 %.

## Photovoltaic Modules and Power Plants

We develop industrial connection technology for the new generations of solar cells. A further focus is on the integration of PV into different applications, currently with product development and testing, potential studies (BIPV, FPV) and an application guideline. Our CalLab PV Modules was accredited as an independent calibration laboratory with the internationally leading value of only 1.1 % for the measurement uncertainty.

525
Total staff

113
Journal articles and contributions to books

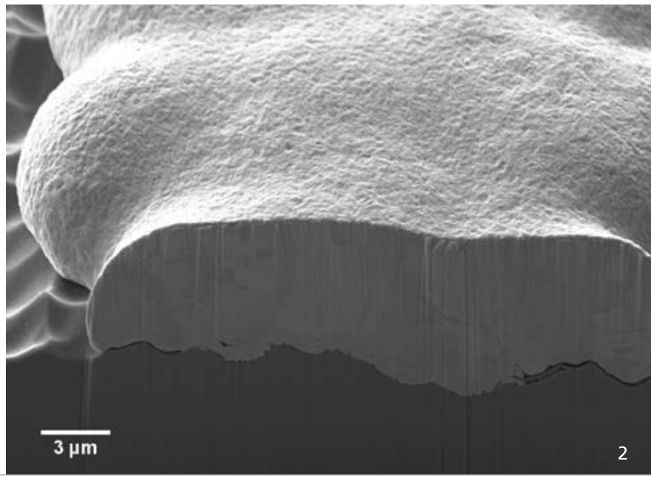
161
Lectures and conference papers

9
Newly granted patents

Our newsletter offers regular updates on our research milestones.

www.ise.fraunhofer.de/photovoltaics

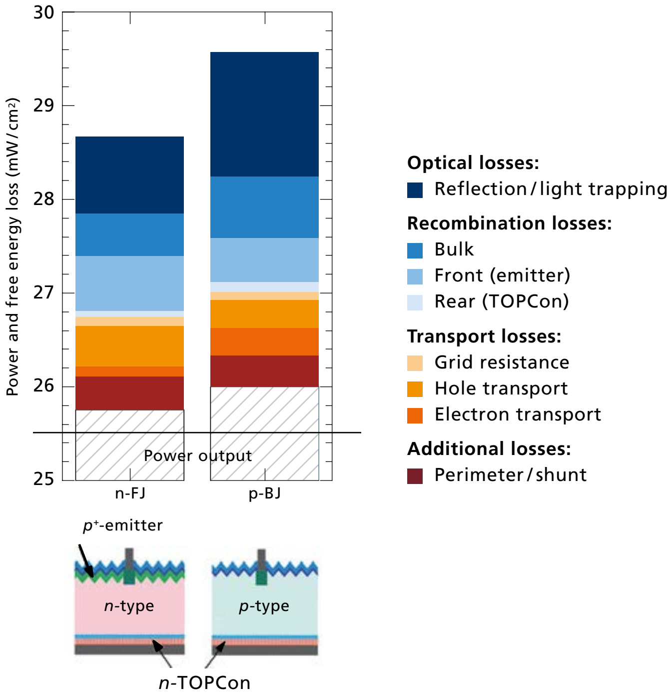
Photo: Highly efficient shingle solar cells in a car roof.


## TOPCon: From 26 % Laboratory Cells to Industrial Maturity

In order to achieve the highest efficiencies of silicon solar cells, it is mandatory to implement passivating contacts that minimize the recombination of charge carriers. One prominent example is the TOPCon technology (Tunnel Oxide Passivated Contact) developed at Fraunhofer ISE. As this contact system has a low optical transmittance, it is usually implemented on the back surface of the cell. By combining a transparent front surface, including a boron emitter, with an excellently passivated back surface, we have achieved an efficiency of 25.8 % ($V_{OC}$ = 724 mV) for a small cell area on an *n*-type wafer. Now, we have transferred the processing sequence for this laboratory cell to one that can be implemented completely industrially. Within a year, we succeeded in increasing the efficiency of these industrial TOPCon solar cells with screen-printed contacts to 23 % (cell area: 244 $cm^2$). In addition, a large TOPCon cell featuring electro-plated copper contacts was produced with an efficiency of 22.7 %. Increasing the efficiency to more than 23.5 % will be possible soon by simple improvements in the process without increasing its complexity.

An analysis of the cell type based on numerical simulation models revealed that recombination at the emitter limited the efficiency and that there was a conflict between the goals of high hole conductivity and low recombination losses in the emitter. These conflicting goals can be elegantly avoided by changing the wafer polarity from *n*-type Si to *p*-type Si: The silicon wafer then supports the transport of holes to the front-surface contact, making the boron-diffused region obsolete. With this concept, we achieved an efficiency of 26 % ($V_{OC}$ = 732 mV) on a laboratory scale. The individual loss mechanisms of this cell were quantified by numerical simulation and are compared to those of the *n*-type TOPCon cell (see graph). The orange and yellow sections of the column clearly demonstrate that – in contrast to the *n*-type cell – the proportion of transport losses due to electrons and holes is well balanced. This cell structure requires fewer production steps and allows using less expensive *p*-type Si wafers. It is thus a very attractive alternative to the *n*-type TOPCon cell and demonstrates that solar cells with contacts on both surfaces can also achieve efficiencies exceeding 26 %.




Graph: Breakdown of the electrical and optical power losses of *n*-type and *p*-type TOPCon solar cells.

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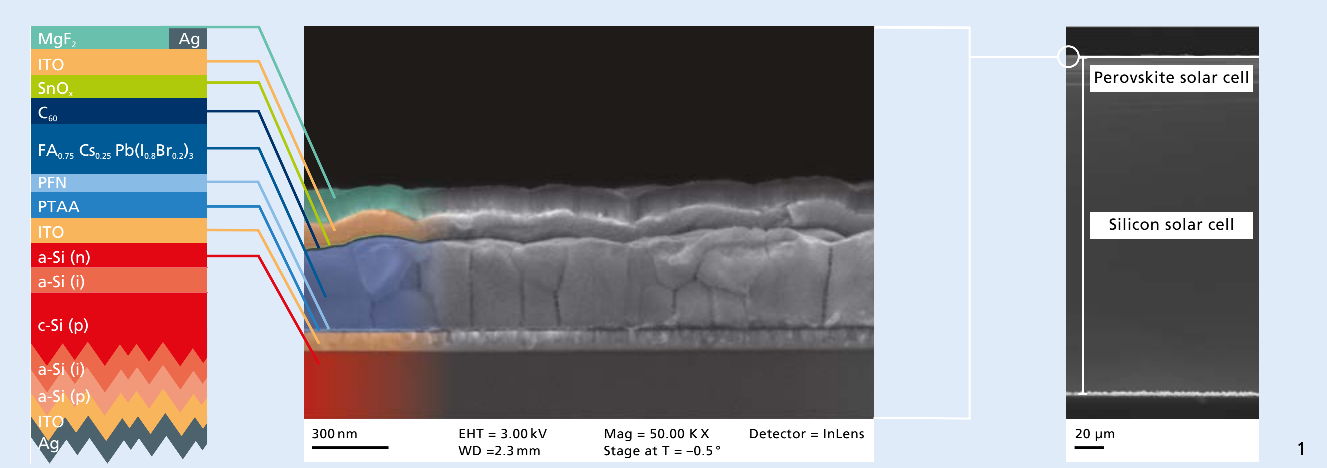
1 Front surface of an industrial TOPCon solar cell.

2 Scanning electron microscope image of an electro-plated metal finger on a TOPCon surface.




## Cost-Effective and Resource-Efficient Perovskite-Silicon Tandem Solar Cells

Perovskite-silicon tandem solar cells promise lower levellized costs of electricity and lower resource consumption than conventional silicon solar cells due to their higher efficiency. The perovskite solar cell for the tandem stack is deposited directly onto the silicon solar cell. As the perovskite semiconductor features a band gap of higher energy than silicon, the perovskite solar cell can convert high-energy photons more efficiently than the silicon solar cell. In turn, the silicon solar cell can use the lower-energy photons efficiently that are transmitted by the perovskite solar cell. The efficiency increases such that values exceeding 30 % are possible.

Within the "PersiST" project that was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE achieved an efficiency of more than 25 % for a perovskite-silicon tandem solar cell. The silicon solar cell was an a-Si / c-Si heterojunction solar cell with a textured back surface. A layer of indium-doped tin oxide (ITO) created the electrical connection to the perovskite solar cell, onto which we deposited a very thin layer of an organic hole conductor, followed by the perovskite absorber. With the absorber compound $FA_{0.75}Cs_{0.25}Pb(I_{0.8}Br_{0.2})_3$, we realized an optimal band gap of 1.68 eV and achieved high stability. An evaporated film of $C_{60}$, followed by $SnO_x$ and a further ITO layer (Fig. 1) served as the electron contact. In the Fraunhofer Lighthouse project, "MaNiTU", we are now developing this technology further with the goal of achieving yet higher efficiencies. In addition, we are researching lead-free alternatives for the absorber. Assuming that high efficiencies of 28 % and a lifetime of at least 23 years can be achieved for the tandem cells, initial life cycle analyses already identify great ecological added value. Among other aspects, this is because the layers of the perovskite solar cell are very thin and the higher efficiency significantly reduces the $CO_2$ footprint needed to generate a kilowatt-hour of electricity.

The situation with the levellized cost of electricity is similar: It is predicted that additional layers for the perovskite solar cell can be produced very cost-effectively. The efficiency increases significantly and the cost per kilowatt-hour of electricity decreases. In a comprehensive cost analysis, we determined that perovskite-silicon tandem solar cells are particularly promising for applications in rooftop systems and other area-limited applications and present a significant cost advantage compared to purely silicon solar cells. The precondition is that the perovskite technology reaches a level within the next five to six years where the efficiency of industrially produced tandem solar cells exceeds 30 %. To do so, it will be necessary to implement cost-effective processes and raise the module lifetime to values comparable to those with silicon solar cells.

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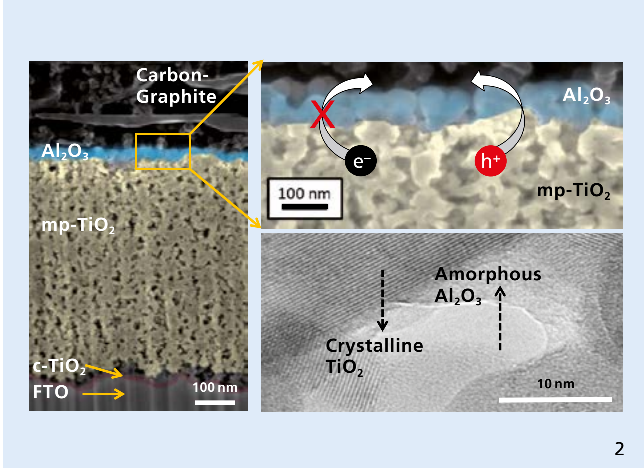
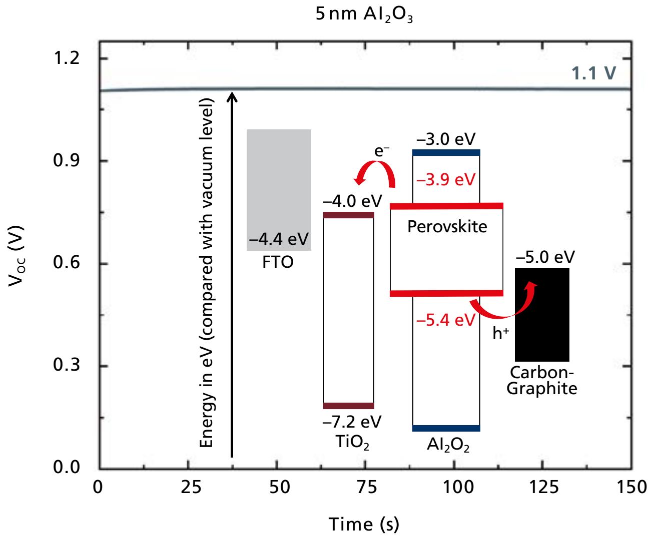
1 Structure (left) and electron microscope image (right) of the perovskite-silicon tandem solar cell. Compared to the silicon solar cell, the perovskite solar cell is very thin.




## $Al_2O_3$-Passivation Layers for Printed Perovskite Solar Cells

The research field of perovskite solar cells is attracting increasingly strong interest around the world. Solar efficiencies of up to 25.2 % have already been achieved for single cells, which nonetheless are generally based on unstable organic passivation layers and laboratory methods that cannot be upscaled. Therefore, Fraunhofer ISE quickly set itself the goal of developing modules that could be printed over large areas and consisted of perovskite solar cells containing stable inorganic passivation and electrode layers.

The combination of an electron-selective electrode layer of porous nano-scale $TiO_2$ with a porous back-surface electrode layer of graphite has proven to be particularly promising. The perovskite is subsequently introduced into the open layer structure from a solution and crystallized. When illuminated, charge separation occurs here, in which the transport of electrons from the $TiO_2$ into the graphite particles of the back-surface electrode must be prevented to suppress unwanted interfacial recombination. With this concept, Fraunhofer ISE has already achieved a certified efficiency of 15.5 %, which is currently the world record for printed solar cells. We have demonstrated that sputtering an extremely thin passivation layer of aluminium oxide ($Al_2O_3$) onto the porous surface of the nano-scale $TiO_2$ layers can increase the photovoltage significantly. The $Al_2O_3$ acts as an electric insulator without destroying the porosity that is needed to introduce the perovskite. Under the electron microscope, we have detected the formation of a 5 nm surface film of amorphous $Al_2O_3$ on the crystalline $TiO_2$. In addition to the nano-scale coverage, pinhole defects in the printed electrode layer are insulated during the sputtering, which benefits the large-area insulation. The implemented passivation results in a high photovoltage of 1.1 V (see graph), which is only 100 to 150 mV lower than the highest reported photovoltages for perovskite solar cells with organic hole conductors. The work is thus extremely relevant for further upscaling of highly efficient, durable perovskite solar modules.




Graph: Stabilized photovoltage $V_{OC}$ of perovskite solar cells including an $Al_2O_3$ passivation layer. Insert: separation of photo-generated electrons and holes.

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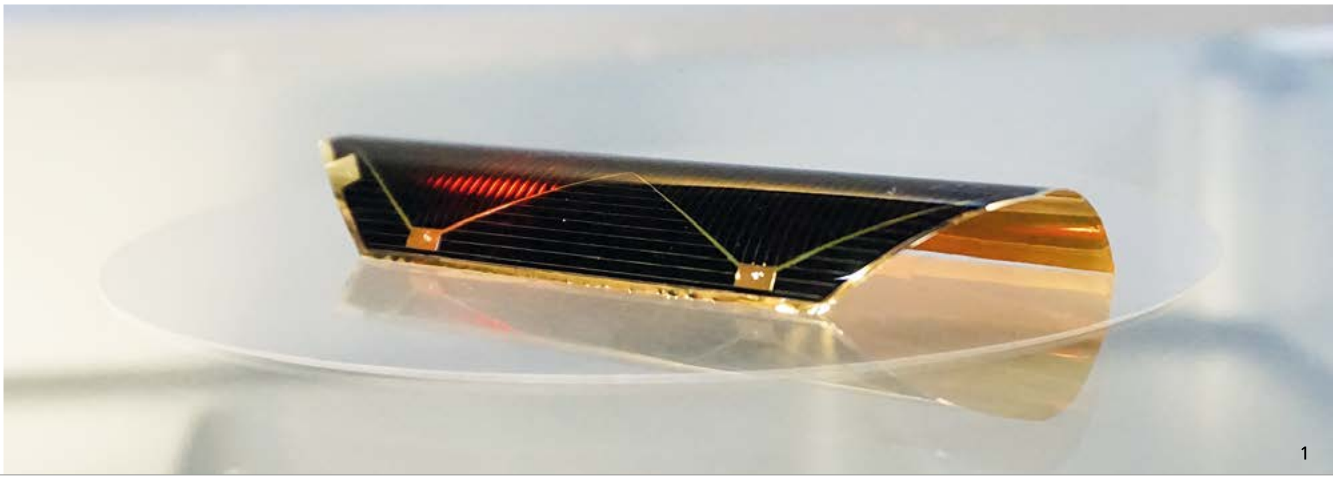
1 Screen-printed photoelectrode of a perovskite solar module.

2 Layer stack and aluminium oxide passivation layer of a printed perovskite solar cell.



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## Flexible III-V Solar Cells for New Aerospace Applications

Highly efficient III-V multi-junction solar cells have been applied as the standard for many years to supply satellites with power. To produce the cells, thin III-V films of only a few micrometers are deposited onto rigid germanium substrates that are typically several 100 micrometers thick. Alongside conventional satellites, new applications and business perspectives are currently emerging in the aerospace industries. The possibilities are manifold: They range from constellations of hundreds of small satellites in near-earth orbits ("New Space"), e.g. for global coverage with satellite-based Internet connection, through unmanned, quasi-stationary pseudo-satellites ("High-Altitude Pseudo-Satellites" HAPS), to electric aeroplanes.

In addition to high efficiency, meaning high power per area ($W/m^2$), minimal weight or high power per mass (W/g) is always decisive for these applications. Furthermore, the solar cells must be flexible, so that they can be integrated into curved wings without impairing the aerodynamics. For the emerging aerospace markets, the production costs for these solar cells also represent an essential factor.

At Fraunhofer ISE, we are working together with our partners on technological solutions for these new markets. In the EU-funded "ALFAMA" project, we have developed a III-V triple-junction solar cell in thin-film technology (Fig. 1). The GaInP/GaAs/GaInAs solar cell layers, which are only a few micrometers thick, are separated from the GaAs substrate by a wet-chemical process ("epitaxial lift-off") and subsequently transferred onto a thin metal foil. With a specific mass of only 13.3 $mg/cm^2$, the cell is four to five times lighter than typical space solar cells, accompanied by a power per mass ratio of 2.76 W/g. In addition to the low mass, the epitaxial lift-off process offers the advantage that the valuable substrate can be used many times. In the EU-funded "SiTaSol" project, we have developed a simple wet chemical process to recondition GaAs substrates after the solar cell layers have been lifted off. We demonstrated that comparable material quality to that of the original substrate was achieved when a reconditioned substrate was re-used. In the "LightBridge" project that is supported by the German Federal Ministry for Education and Research (BMBF), Fraunhofer ISE is also developing an accelerated epitaxial lift-off procedure, in which the hydrofluoric acid that is used for separation can not only enter from the sides, but also through pre-structured channels in the semiconductor layers. By applying this method, we succeeded in completely separating a 4" wafer within less than two hours.

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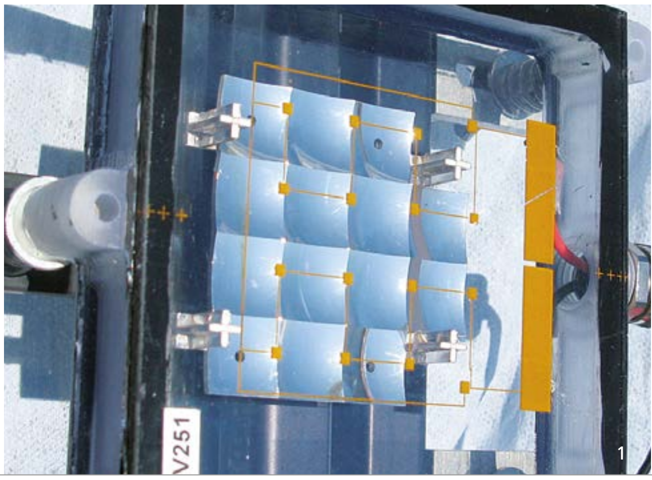
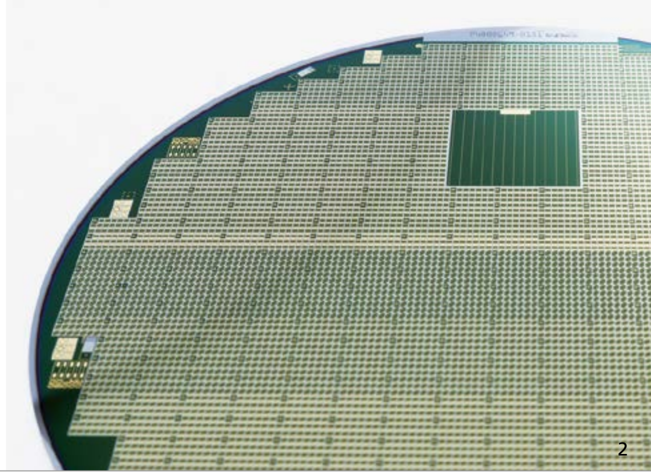
1 Curved thin-film triple-junction solar cell with an area of 20 $cm^2$. III-V layers grown at Fraunhofer ISE were transferred by epitaxial lift-off onto thin metal foil by our partner, tf2 devices (Nijmegen, Netherlands).

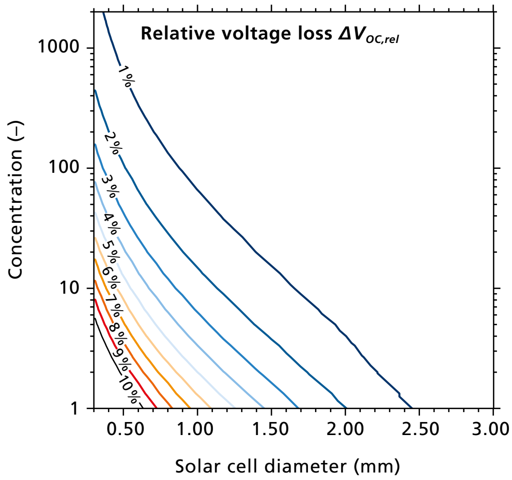



## Miniaturization in Concentrator Photovoltaics (µ-CPV)

Concentrator photovoltaics (CPV) achieves the highest efficiencies and lowest energy payback times of all photovoltaic technologies. Its industrial implementation has already been demonstrated in numerous multi-MW power plants. However, to ensure competitiveness, the module costs need to be reduced further. Miniaturization and innovative production technology from other branches, such as micro-electronics, opto-electronics and display manufacturing, promise new module concepts with high cost-reduction potential. Miniaturization demands that thousands of components be positioned and contacted accurately over large areas. To this purpose, additive manufacturing processes and parallelized placement and contacting processes are applied. Furthermore, use is made of self-alignment effects.

In the "HeKMod4" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), we have developed a miniaturized CPV module with reflective mirror optics (12.8 mm side length of a unit cell) and concentrator solar cells with a side length of only a few 100 micrometers. We have demonstrated that the effect on electric performance due to increased perimeter recombination under highly concentrated sunlight is negligible even for micro solar cells with an edge length of only a few hundred micrometers (see graph). The "micro-CPV" project, which is also funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), is building on these results. Here, we are developing a micro-CPV module based on a holistic approach that takes into account optical, electrical, mechanical and production-technological boundary conditions. The goal is to achieve highest efficiency and high acceptance angle, i.e. tolerance to solar-tracking errors, despite low-cost manufacturing processes. The




Graph: Relative loss in open-circuit voltage $V_{OC}$ due to increasing influence of perimeter recombination (relative to $V_{OC}$ of a circular concentrator solar cell with 3 mm diameter).

base plate of the module consists of a glass-based panel, which is produced by additive circuit board technological processes. Miniaturized concentrator solar cells with an area of only a fraction of a square millimeter are placed directly on the panel as bare dies and align themselves by surface tension forces when the solder melts. The front surface of the chip is contacted electrically by additive printing technology. A lens array concentrates the sunlight by a factor of a thousand onto the micro solar cells. Spherical glass lenses positioned in parallel on the solar cells homogenize the illumination of the cells and increase the acceptance angle. Due to the efficient dissipation of the heat load, which has been reduced by miniaturization, we expect operating cell temperatures of less than 80 °C, despite the 1000-fold solar concentration and the absence of a dedicated heat sink.

1 Miniaturized CPV module with reflective mirror optics (12.8 mm side length of a single optics unit) from the "HekMod4" project.

2 Thousands of micro concentrator solar cells on a 4" wafer, which was processed in the "micro-CPV" project by the partner, AZUR SPACE Solar Power GmbH.

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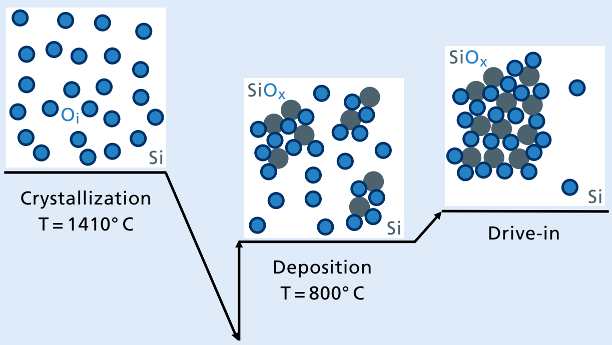

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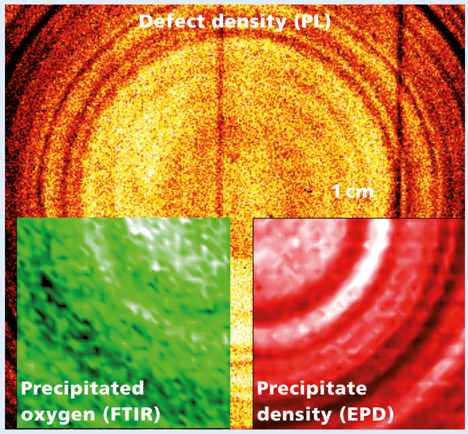

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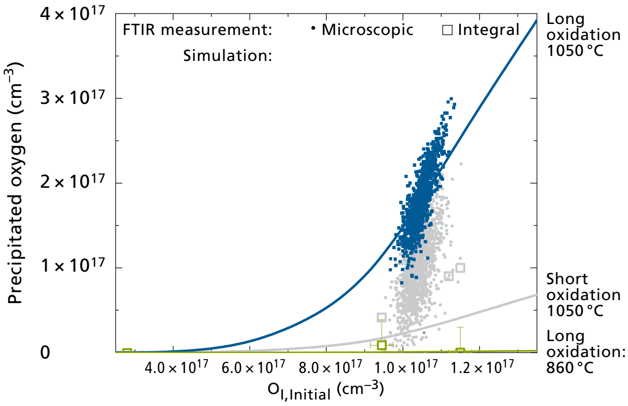
## Material Limitation Due to Oxygen Precipitation in Solar Cells

In silicon wafers with high oxygen concentrations, recombination-active oxygen precipitates form during the solar cell processing, which lead to noticeable degradation of the solar cell efficiency. The oxygen is introduced via the crucible during the Czochralski process and is initially present in a soluble form that does not affect recombination. Due to the cooling after crystallization and the doping process at about 800 °C, the dissolved oxygen becomes oversaturated and forms small oxygen precipitates (Fig. 1). If these precipitates are sufficiently large, they grow during further high-temperature processing steps into very large and thus lifetime limiting precipitates, which create annular defect zones on the wafer (Fig. 2). To identify these defects unambiguously as oxygen precipitates, we at Fraunhofer ISE combined imaging photoluminescence (PL) for charge carrier lifetime or defect density measurement with well-known methods for oxygen precipitate analysis from the semiconductor industry. We selected the following methods:

» Application of a microscopic counting method to determine the etch pit density (EPD), which forms in the stress field of oxygen precipitates in SECCO etches
» Fourier-transform infrared spectrometry (FTIR) to measure the decrease in dissolved oxygen or the concentration of precipitated oxygen during solar cell processing

By adapting both methods to approximately 150 µm thin, unpolished wafers, it was possible to demonstrate an unambiguous local correlation between defect density, precipitate density and precipitated oxygen concentration on industrially processed solar cell wafers for the first time (Fig. 2).




Graph: Comparison of measured and simulated interstitial oxygen loss versus the initial oxygen concentration $O_{i,initial}$.

For detailed modelling of oxygen precipitates, we also transferred insights from the semiconductor industry to the much shorter processing sequences for solar cells, taking surface effects of the thin wafers and the influence of the gas atmosphere in new kinetic precipitation models into account. The good agreement between simulations and measurements of the precipitated oxygen concentration in the graph illustrates the successful result of considering these effects. These studies, in which we cooperated with the University of Freiburg within the "Genesis" and "Limes" projects that were funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), also had the goal of predicting the lifetime limitation in solar cells due to oxygen precipitates. To achieve this, we combined the kinetic model with calculating the charge carrier recombination at oxygen precipitates, taking the precipitate size into account.

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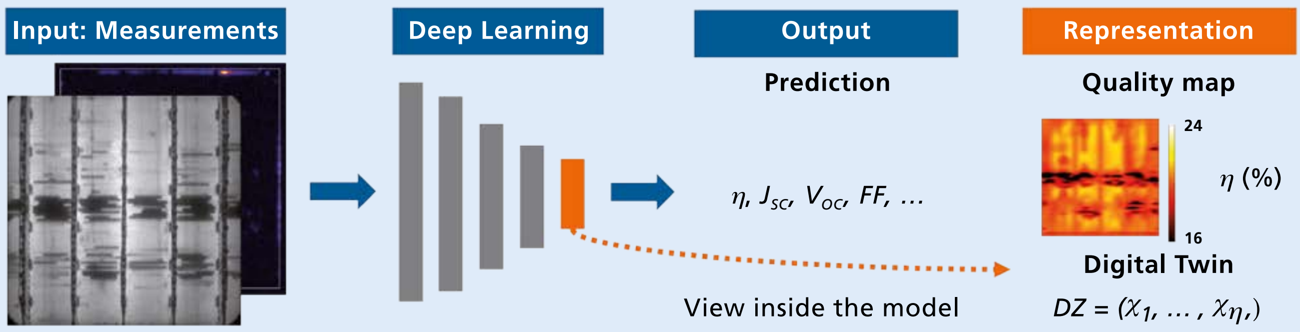
1 Dissolved oxygen forms small precipitates, which grow into large, harmful oxygen precipitates during high-temperature processes.

2 Comparison of PL, FTIR and EPD measurements demonstrates the correlation between recombination-active defects and oxygen precipitates.

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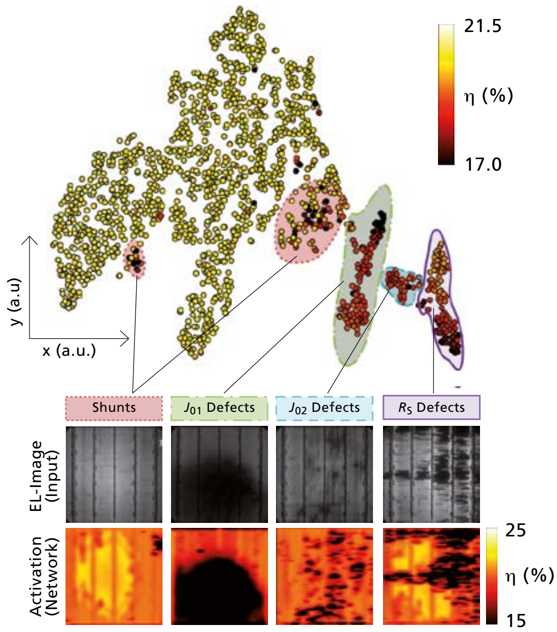
## Artificial Intelligence for Solar Cell Characterization

Quality inspection based on spatially resolved in-line measurement data opens new opportunities for process control in PV production. Image-processing methods that are currently commercially available are based on manually defined algorithms, which can treat only a fraction of the available information due to the complex interrelationships between the data. Thus, within the "NextTec" project that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE is investigating artificial intelligence (AI) methods to derive a digital model ("digital twin") of the solar cell from the measurement data.

The digital twin should learn the essential information concerning quality from empirical data. To this purpose, electroluminescence (EL) and thermography measurements are connected via "deep learning" to predict physical parameters defining quality. The model learns an informative description of the condition of the solar cell by deriving a compact representation of the data from the multi-dimensional measurement images, which enables successful quality prediction. A glance at the model shows the activation of the neurons. On the one hand, these reflect the expected, spatially resolved distribution of quality from the network perspective with a "quality map" and thus allow drawing conclusions about the cause and effect of defects. On the other hand, the compact model representation allows the data to be stored efficiently and compared for the purpose of rapid defect classification.

In the presented example, our AI model learns the derivation of a digital twin on the basis of a data set from 1600 cells. For illustration, the representations of the investigated solar cells are viewed in a two-dimensional figure. The figure was simplified such that the representation of neighboring points is similar: Clusters form, consisting of solar cells that exhibit specific defects.




Graph: Low-dimensional embedding of empirical loss analysis. Samples with similar defects are identified in the graph by a single background color. An EL image with the quality distribution anticipated by the neural network is shown for each cluster.

These are identified by a colored background. For qualitative analysis, a typical EL image is shown for each defect group. Each of these images is accompanied by a quality map with the reverse-calculated, spatially resolved efficiency, which is lower in defect-rich regions. The described technique can be used to classify cells automatically and to sort out samples with specific representations or defect groups. Spatially resolved assessment of defect severity based on quality maps can make an additional contribution to process optimization.

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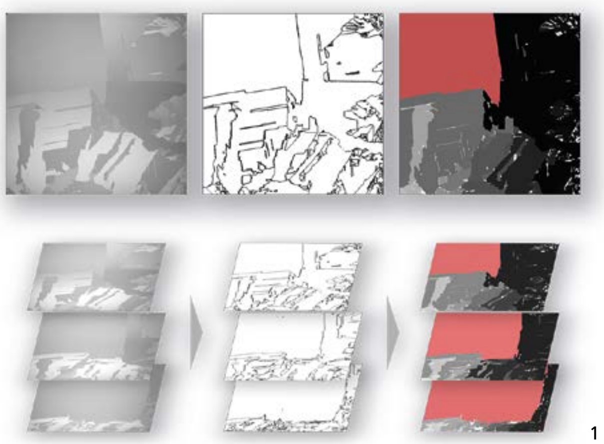
1 Approach to assess spatially resolved quality data via artificial intelligence.



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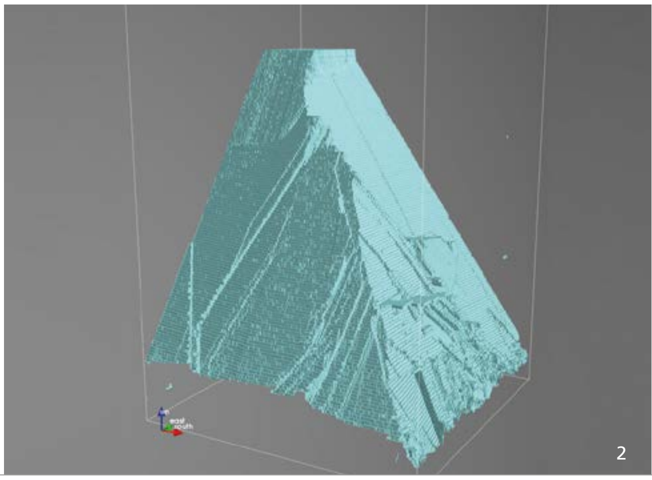

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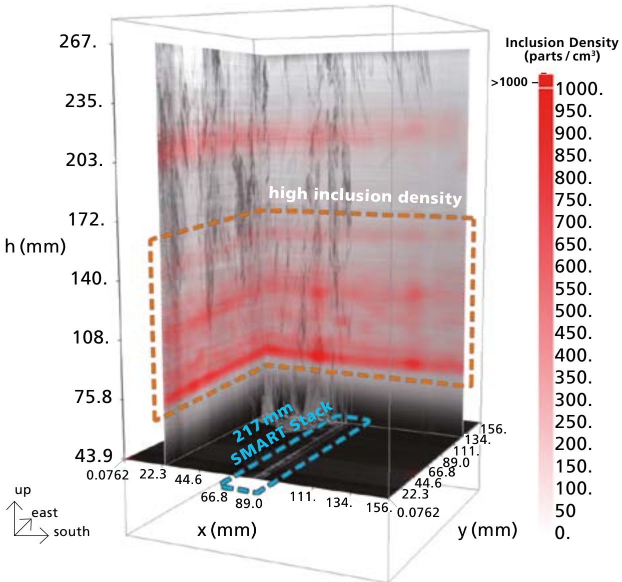
## New Insights into the Growth of Crystals and Defects

Investigating new silicon materials produced by directional solidification with a nucleation template must be based on a detailed understanding of the origin and development of crystalline structure and defects. Implementing innovative crystallization processes in production also demands iterative optimization of the crystallization procedure and thus monitoring of the process. Approaches that enable the crystal growth to be controlled and analysed quickly and efficiently are thus very important.

Fraunhofer ISE has developed an analytical platform that allows the internal crystal structure of a cast silicon brick to be visualized rapidly and in detail on the basis of brick and wafer data. Whereas conclusions about the grown structure and necessary process adaptations were often drawn based on the brick surface or unprocessed 2D images after wafering, the new process gives a plastic, naturalistic insight into the spatial growth of crystals and defects via different 2D and 3D visualization techniques. Intelligent data management, optimized presentation and simple operating concepts allow intuitive navigation through the measured data for a brick and concentrated analysis of the physical structure. In addition, the combination of different data sets makes it feasible to study interactions between grain boundaries and defects in greater detail. For example, as part of our further development of the cast monocrystalline silicon process, we have deliberately introduced functional defects into the crystal with special nucleation templates and the so-called "SMART" technique in order to prevent undesired crystal structural defects from originating and growing. We can inspect and analyze their effect and mutual interactions with appropriate visualizations (see graph). The platform is open for other types of data and can be extended with further visualization and analytical methods.




Graph: PL data (grey) and inclusion density (red) of a cast monocrystalline edge brick, visualized by cut planes. "SMART" defects keep dislocations away from the monocrystalline part.

The analytical platform is based on a multifaceted image processing chain to extract and reconstruct defects from photoluminescence and grain boundary images of wafers generated over the course of several years in the "Q-Wafer" and "Q-Crystal" projects. In contrast to older, destructive techniques, the new procedure can be applied directly for production control, as in-line measurement data on the raw wafer suffice for 3D reconstruction of the crystal structure and its defects.

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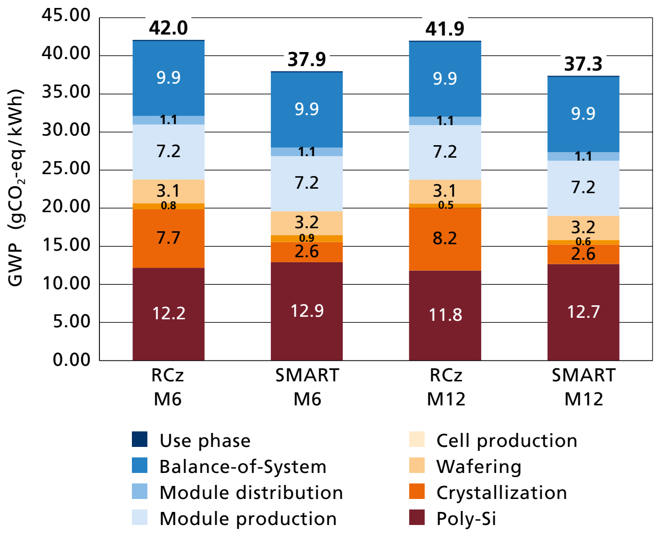
1 Reconstruction of grains of a cast monocrystalline brick. Left: optical measurements, center: extracted grain boundaries, right: 3D grain segment tracking.

2 Main grain of a cast monocrystalline corner brick in an interactive 3D visualization.

## Development of Cast Monocrystalline Silicon with a Small $CO_2$ Footprint

As an alternative to the established Czochralski process (Cz-Si) for drawing monocrystalline ingots, we are working at Fraunhofer ISE on the cost-effective and resource-conserving production of monocrystalline wafers by the cast monocrystalline process. By combining large seeding templates with thin strips of silicon according to the SMART concept (Seed Manipulation for Artificially controlled defect Technique), we produced material with deliberately introduced functional defects that features a strongly reduced number of unwanted crystalline structural defects. In this way, we have produced full-square, monocrystalline wafers with an edge length of 210 mm, which form the basis for the newest generation of solar cells. Applying an industrially relevant solar cell process, we achieved the same efficiency level of just on 22 % for these wafers as for wafers from the Czochralski process.

In a cost and carbon balance analysis for the entire value chain, we investigated the economic and ecological sustainability of using cast monocrystalline silicon wafers for the production of PERC solar cells and their subsequent usage in a photovoltaic system and compared it to the values for Czochralski silicon wafers. The cast monocrystalline technology based on a G8 industrial furnace and a Cz crystallization facility with 36” crucible size and recharging procedures (recharging Cz, RCz) were modelled. We analyzed the Global Warming Potential (GWP) and the costs per wafer for two relevant formats (M6: 166 × 166 mm$^2$, M12: 210 × 210 mm$^2$). Calculations for a PV system with modules which each consist of 138 PERC half-cells from cast monocrystalline wafers show a reduction of 9 % in the GWP for an assumed utilization phase of 25 years. The cost profiles for the wafers from the two technologies intersect at about 5 to 7 cents (US $) per kilowatt-hour electricity and indicate cost advantages for cast monocrystalline wafers in the case of higher electricity tariffs. Furthermore, an increase in the brick yield from currently app. 53 % to above 60 % would lead to a significant reduction of the wafer costs by up to 0.4 cents per peak watt. Thus, the cast monocrystalline technology presents a promising alternative to the currently dominant RCz technology, particularly from the perspective of sustainable value chains.




Graph: Global warming potential GWP for both crystallization technologies and wafer formats produced by the calculated PV system considering a service life of 25 years.

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1 Monocrystalline seeding templates in a laboratory crucible, arranged according to the SMART cast monocrystalline technique.

2 Full-square monocrystalline wafers from a cast monocrystalline ingot of M6 format with an edge length of 166 mm.

## Silicon Heterojunction Technology (HJT) Platform at Fraunhofer ISE

Silicon heterojunction technology (HJT) solar cells make record cell efficiencies exceeding 25 % feasible and thus are counted, together with polycrystalline silicon-based passivating contacts (TOPCon), among the most promising technologies of the next generation. The interest of the photovoltaic industry in HJT technology has increased recently, resulting in growing market shares and production capacity. Solar cell production, which is being established anew in Europe, applies HJT for both simple solar cells and for the bottom cell of Si-perovskite tandem solar cells.

Fraunhofer ISE addresses the complete processing sequence for HJT technology from Si wafer input control tests through to module production and quality control. The Institute works continuously on optimizing specific single processes and interfaces and developing new technological approaches. Apart from increasing efficiency, the R&D activities aim particularly to reduce production costs and increase the productivity of the equipment used.

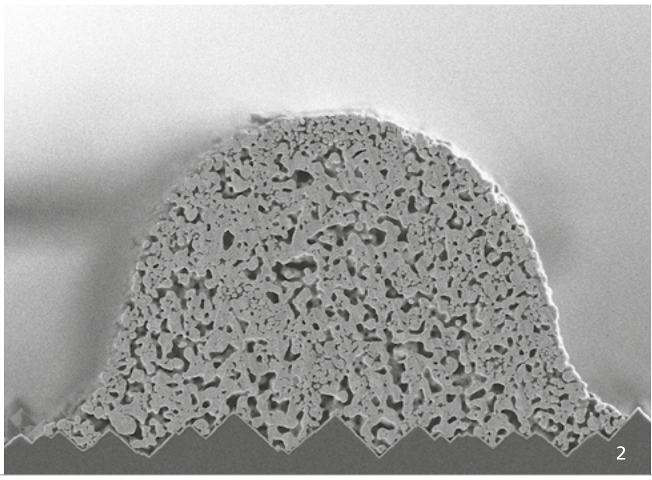
In the PV-TEC front-end laboratory at Fraunhofer ISE, our current work focusses on the further development of processes and equipment technology for wet-chemical surface structuring, cleaning and conditioning, as well as plasma-based deposition of amorphous silicon (a-Si) layers and transparent conductive oxides (TCO). Specific research topics include fine-tuning of the a-Si and TCO layer stack regarding passivation and contact properties, approaches to save indium by using capping films for partial substitution of the TCO layer and multi-functional capping layers that enable new processing routes and contribute to efficiency improvements of complete cells and half- or shingle cells. The experimental work is supported by simulation of processes and devices.

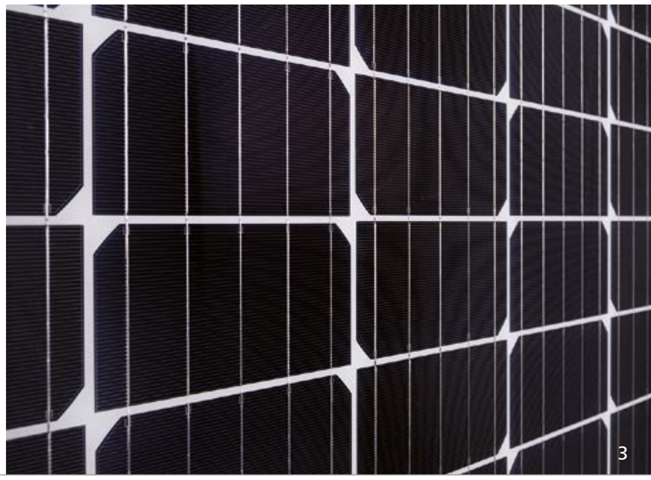
In the PV-TEC back-end laboratory, we evaluate different innovative metallization processes such as fine-line screen printing, multi-nozzle dispensing, FlexTrail printing, laser transfer printing and rotary printing processes. We have succeeded in reducing the resulting structure widths over the past few years: They are less than 10 µm in the laboratory today. As a result, the silver consumption was reduced significantly.

In addition, we develop alternative, silver-free metallization approaches especially for heterojunction solar cells. In both the "NOBLE" (Native Oxide Barrier Layer for selective Electroplating) and the Laser Transfer and Firing (LTF) processes, copper is deposited galvanically onto a metallic seeding layer. A further focus of current R&D work is on developing of rapid processes to dry or cure the contacts. We successfully demonstrated the application of photonic processes and achieved processing times of only a few seconds.

Half-cells are already an industrial standard today and as the wafer formats continue to increase in size, the separation of cells will become more and more important. To take account of the temperature-sensitive layers and the high efficiency potential of HJT technology, we have optimized the cell separation process specifically for these solar cells. We continue to develop photonic processes to optimize the electrical and optical layer

1 PVD deposition tool with wafers after TCO deposition.





properties and reduce defect states. By developing so-called light-soaking processes in combination with an optimized cell separation process, we have successfully demonstrated an efficiency gain of up to 0.6 $\%_{abs}$.

In the Module-TEC of Fraunhofer ISE, high-efficiency HJT solar cells have already been successfully connected: Both approaches based on smart-wire connection and also those using connectors and conductive adhesives or conventional infrared soldering have been applied.

Conductive adhesives and smart-wire technology make lead-free connection of solar cells without busbars feasible at temperatures of approximately 150 °C. The application of cylindrical wire for wire-based connection and structured connectors with conductive adhesives achieved an increase in module performance of approximately 1.5 %. To ensure the long-term stability of module encapsulation, our research activities concentrate on eliminating moisture by using glass-glass modules with edge seals, developing glass-backsheet modules with moisture-resistant backsheets and applying gentle and rapid low-temperature lamination.

The German Federal Ministry for Economic Affairs and Energy (BMWi) funded the "PV-BAT-400", "ProSelect", "HJT 4.0", "DYNASTO", "Smart" and "CUSTCO" research projects, in which we further developed many important individual aspects of the HJT processing sequence and demonstrated new approaches, both within the Institute and in close cooperation with our project partners from industry and research.

Since 2020, the laboratories of Fraunhofer ISE have covered the complete range of HJT processing technology. Applying our HJT base process with screen-printing metallization, we demonstrated maximum cell efficiencies of 23 % on large-area M2 wafers and had the values confirmed by the CalLab of Fraunhofer ISE. As the first research institute, we have successfully proven applying our optimized processing route from full to half cell, whereby it is even possible to increase the efficiency of an HJT half-cell module in comparison to a full-cell module.

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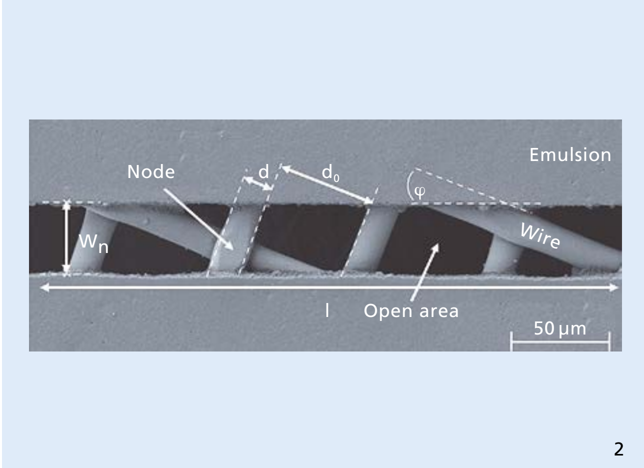
2 Scanning electron microscope image of a metal contact on an HJT solar cell.

3 HJT half-cell module with five cell connectors, connected with a conductive adhesive.

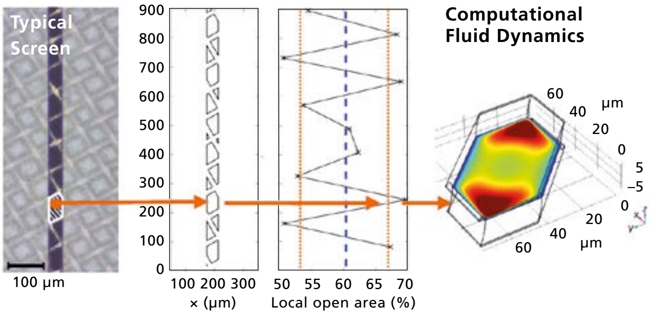



## Digitalization of Accurate High-Throughput Printing Processes

As part of the digitalization of production and business processes, it is necessary to develop digital models of workpieces and production processes. These so-called "digital twins" are based on physical modelling and/or simulation of the real item. To implement digital twins for high-throughput metallization of solar cells, it is decisive to reproduce the complexity of flatbed and rotary screen-printing processes with all of their critical features.

At Fraunhofer ISE, we initially developed a simulation algorithm for this task, which, based on any arbitrary screen specification, generates a virtual clone of the relevant screen. This virtual clone is then decomposed by an analytical algorithm into its components and analysed with respect to its functional properties in the printing process. The virtual screen is introduced into a computational fluid dynamics (CFD) simulation and then tested in a virtual screen-printing process. This type of CFD simulation needs a detailed model of the rheological behavior of the investigated printing paste. We have developed special characterization methods that reproduce the rheology of pastes with a high metal content at an adequate level of detail. The results of the CFD simulation are input to the analytical algorithm, which can then automatically introduce changes to the screen architecture. At present, we are working on making these physical simulation models more efficient and applicable to a greater bandwidth of rheological parameters. The goal is to use the model in a next step to train artificial neural networks.

In addition, we plan to test these solutions not only in flatbed but also in rotary screen-printing processes. Within the "Rock-Star" and "Rock-It" research projects funded by the German Federal Ministry for Education and Research (BMBF), we have developed an industrial high-throughput demonstrator system that provides an ideal platform for this work. It is equipped with an innovative transport system based on autonomous shuttles with their own power supply and a high-speed camera system to orient the wafers accurately for the printing process. At present, it enables a throughput of up to 8,000 wafers per hour, which corresponds to double the rate per track for modern flatbed screen-printing lines. The newly developed equipment concept opens numerous further application fields for high-throughput coating of precision components such as fuel cells, circuit boards or electronic components.




Graph: Digital representation of a screen and its implementation in a CFD screen-printing model.

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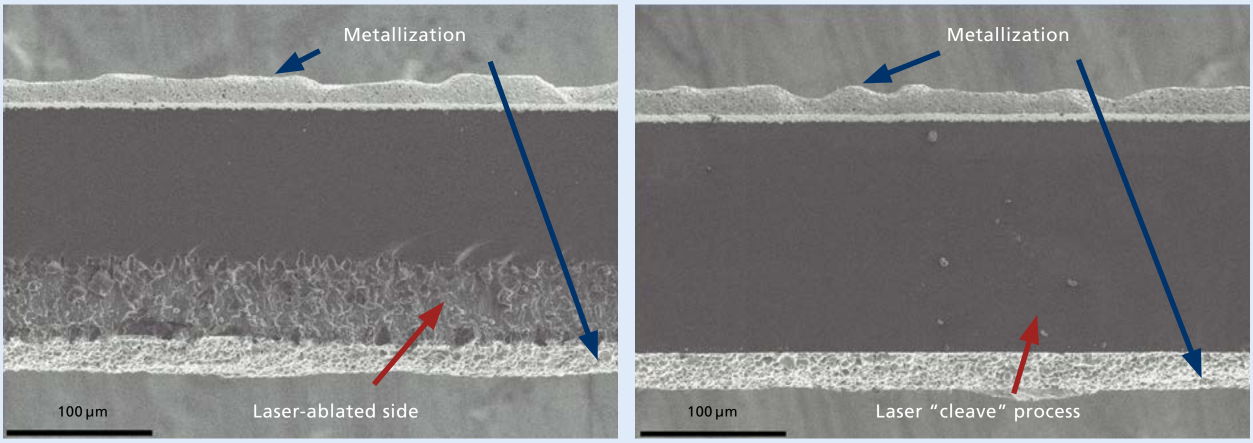
1 "Rock-Star" demonstrator equipment for high-throughput metallization using rotary printing.

2 SEM image of a regular screen opening.

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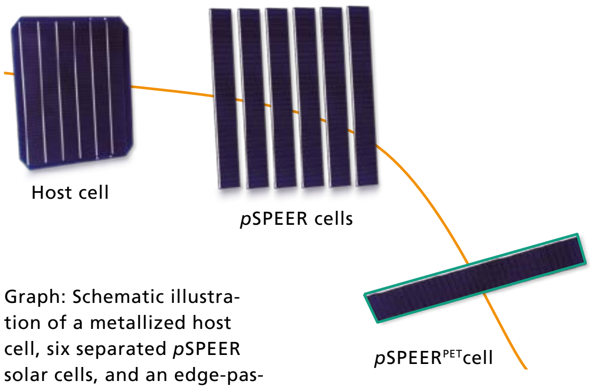
## Separation and Edge Passivation of Silicon Solar Cells

The market share of separated silicon solar cells such as half cells and shingle solar cells has increased rapidly in recent years. One of the reasons is that the lower current from smaller separated cells reduces the cell interconnection losses.




Graph: Schematic illustration of a metallized host cell, six separated *p*SPEER solar cells, and an edge-passivated *p*SPEER$^{PET}$ solar cell.

Separation usually occurs after completion of the so-called "host cell" in full wafer-sized format. This host cell corresponds to the final cell product and features a metallization configuration that corresponds to the dimensions of the separated solar cell. However, the separation of host cells also leads to newly formed, not passivated cell perimeters with edge defects. These cause so-called edge recombination, which reduces the cell efficiency. The edge recombination scales proportionally to the perimeter-to-area ratio. The higher the efficiency potential of the original cell, the greater is the significance of this additional loss. At the cell level, the edge recombination can be reduced by shielding the charge carriers of one polarity from the edge and/or reducing the defect density at the edge.

The "PV-BAT400" project at Fraunhofer ISE has the goal of producing modules with very high power density by shingling bifacial solar cells. To this purpose, we applied to the concept of separated shingle solar cells to a bifacial "passivated emitter and rear cell" (PERC) with a *p*-doped base (called *p*SPEER). In a first step, we worked with two laser-based separation techniques, laser scribing and mechanical cleaving (LSMC) and thermal laser separation (TLS). Subsequently, an industrially compatible technology for edge passivation, the "passivated edge technology" (PET) was developed and applied on a laboratory scale. The PET comprises the deposition of aluminium oxide and its thermal activation. To avoid damaging existing metal contacts and passivation layers, we optimized the process such that low temperatures below 200 °C suffice for deposition and activation. On this basis, a shingle cell that had been separated by TLS and passivated by PET (called *p*SPEER$^{PET}$) achieved a 4 W/m$^2$ higher power density compared to a conventional LSMC-separated shingle cell without PET. The most efficient *p*SPEER$^{PET}$ solar cell to date features a bifacial power density of 237 W/m$^2$ (irradiance of 1000 W/m$^2$ on the front and 100 W/m$^2$ on the back). The cells are now being integrated into modules to demonstrate the increase in power density there also. Furthermore, we have tested PET on heterojunction half-cells and were also able to demonstrate the advantage of edge passivation in this respect.

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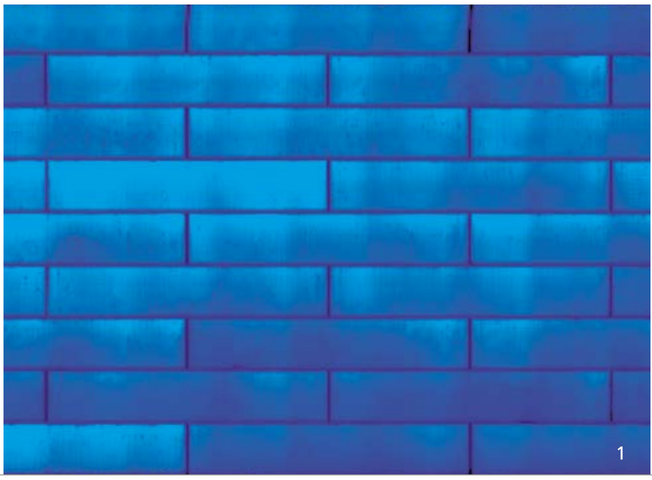
1 Scanning electron microscope images of *p*SPEER cell edges separated by either laser scribing and mechanical cleavage (LSMC; left) or thermal laser separation (TLS; right).



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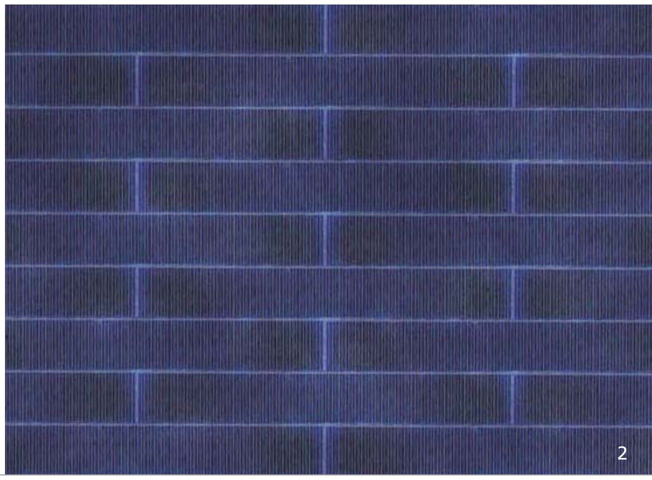

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## Matrix Shingle Technology for Integrated Photovoltaics

One of the primary goals of integrated photovoltaics is to generate PV electricity on a limited area efficiently and reliably. Shingle technology to connect the cells offers great advantages here: When cells are shingled, there are no intermediate spaces, meaning that the area can be completely covered with photovoltaic cells. In this way, the active module area is significantly larger than in a conventional PV module and the module efficiency increases accordingly. An adhesive bond electrically connects the cell strips of rectangular cells in the overlapping regions. Cell connectors are not needed, meaning that optical losses due to shading and resistance losses are lowered. In addition, shingled solar cells are connected without needing lead as an additive. Highly efficient, bifacial shingle solar cells with matrix connection increase the module efficiency by up to 6 $\%_{rel}$, compared to conventional half-cell PV modules.

Together with its industrial partners, Fraunhofer ISE is developing the matrix technology within the "Shirkan" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). We connect the shingle cells by overlapping the long cell edges and displace them laterally with respect to each other as in a brick wall. This configuration avoids inactive areas within the cell matrix and ensures a homogenous appearance as well as maximum utilization of surface area. Within the project, we optimize different module concepts. Furthermore, a stringer is being developed which will achieve a maximum throughput of app. 24,000 shingle solar cells per hour in its industrial implementation.

Initial results on the shading behavior of a matrix shingle module show that – compared to classic shingle string connection – between 70 % and 95 % more power is generated, depending on the scenario. This applies above all for diagonal shading, e.g. by a chimney or a pole, and randomly distributed, small-area shading, e.g. by leaves of a tree. The simultaneous parallel and series connection of the solar cells mean that the current can flow around the shaded area.

In the "Lade-PV" project, which is funded by the same Ministry, we also develop special lightweight PV modules for utility vehicles. Preliminary results indicate that the copper cell connectors used in standard PV modules will probably not withstand the high loads in road transport due to their thermomechanical behavior. An electrically conductive adhesive, which is used to connect the shingle cells, offers more elasticity and thermal stability. The matrix shingle technology also offers great advantages here.

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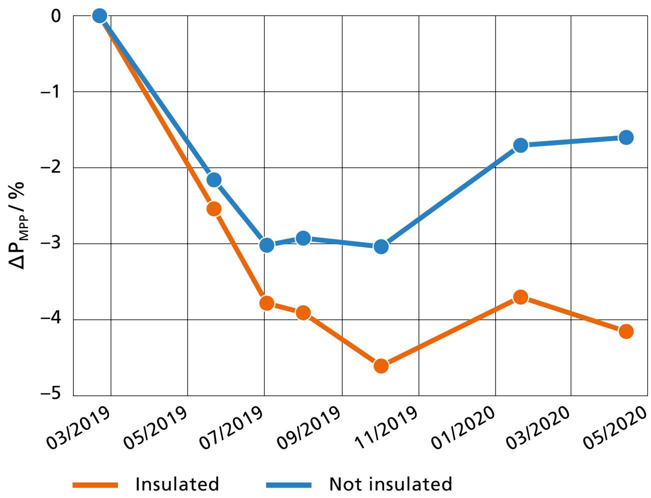
1 Electroluminescence image of a matrix shingle module.

2 A matrix shingle module features maximal area utilization and innovative connection technology.

## Development of Test Procedures – Illustrated by LeTID

As new, highly efficient cell and module technologies are used increasingly in PV power plants, new degradation mechanisms are also emerging. "Light and elevated Temperature-Induced Degradation" (LeTID) is such an effect, creating uncertainty within the PV sector in recent years. The range of susceptibility of commercially available PV modules is large: Whereas we have observed maximum degradation of up to 10 % for some individual modules in laboratory tests, other modules of the same technology display no or very little sensitivity to LeTID. When cost-optimized test procedures are integrated into quality control, module purchasers can reduce the risk of yield losses due to LeTID significantly. In the laboratory, LeTID tests at the module level are usually conducted by injecting current in the dark at an elevated temperature. For the same temperature and charge carrier injection, this stimulates a comparable degradation profile as under illumination.




Graph: Degradation of two identically constructed PV modules with and without rear thermal insulation during one year of outdoor exposure.

Accelerated test procedures must take as little time as possible and be highly relevant for predicting practical operation. In the TestLab PV Modules, Fraunhofer ISE has gained a wide spectrum of test experience for different PV technologies over the past years. Beyond this, we compare different test conditions both among laboratory tests and also with results from an outdoor test. Our results so far show that the conditions (75 °C, current injection from ISC – IMPP) that were originally discussed as part of standardization activities in IEC TC 82 are suitable to assess the LeTID sensitivity of PV modules. Test conditions which significantly shorten the testing times by applying higher temperature or voltage reduce the testing costs but have only limited prediction value for certain cell technologies.

The results from an outdoor test, in which we operated two identically constructed multicrystalline PERC modules at different temperatures by thermally insulating the back surface of one of them, indicate good agreement between indoor test results and behavior in system operation. The higher temperature of the insulated module leads to more rapid degradation. This confirms the major influence of the ambient temperature on-site for the progress of degradation. As a temporary increase in power after the winter months shows, cold periods in Germany lead to recovery effects and thus to further retardation of LeTID.

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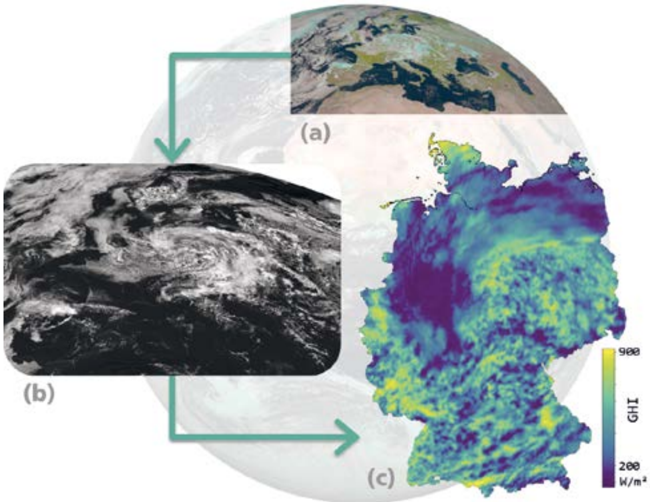
1 PV modules in an LeTID outdoor test.


## Satellite-Based Solar Irradiance Data for PV Applications

Finely resolved information on solar irradiance is essential for the system integration of fluctuating electricity generation by PV. Image data from geostationary meteorological satellites provide an excellent source of information for this purpose due to their high availability and resolution. In energy meteorology, we develop algorithms to calculate and predict the solar irradiance and the resulting PV power. We receive and process satellite images in real time and provide high-resolution irradiance maps for PV power upscaling to transmission system operators. In various projects, we prepare satellite data for specific applications.

To improve predictions of PV (electricity) feed-in, we have cooperated with the transmission system operator TransnetBW to develop a PV generation model that resolves the contribution of individual plants. Based on satellite data, it realistically describes the generation from all PV plants in the control area. In combination with a building-specific load modelling, we have set up a bottom-up model of PV generation, consumption and feed-in for several hundred thousand prosumers. This makes it feasible to analyze the present and future effects of self-consumption on energy balances in detail.

By evaluating cloud movement from satellite images, we can also appreciably improve short-term predictions of PV power based on meteorological models up to a few hours in advance. We have developed an operational system to predict the PV power for a gigawatt PV power station, which integrates satellite-based predictions, local measurement data and numerical weather forecasts. The prediction system is implemented at the plant site and provides the forecasts that are needed for grid integration of the generated electricity.




Graph: Satellite-based irradiance calculation: (a) Satellite image, (b) cloud cover in the image section for Europe, (c) irradiance over Germany (Data: EUMETSAT).

By processing historical satellite data and combining them with GIS data, we develop high-resolution solar cadasters for specific applications. In the "PV2Go" project, we prepare the satellite-based irradiance data to analyze the solar potential of land transport routes. We have developed an operational system for real-time evaluation of vehicle-mounted irradiance measurements, which determines the irradiance along trajectories from satellite data. These data are presented to users in a smartphone app and used for analyses e.g. of shading.

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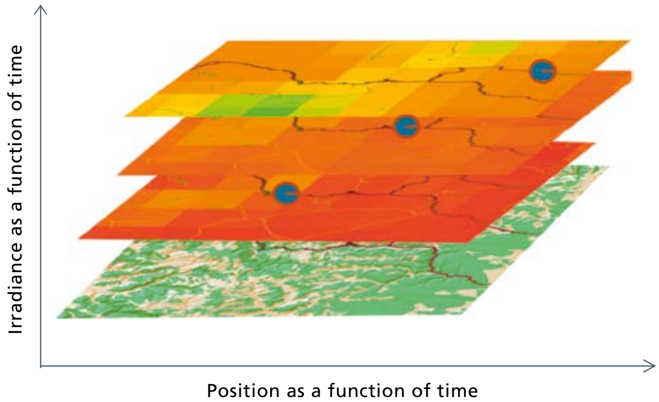
1 Realistic color composite of Meteosat-11 satellite image of Central Europe, 11 July 2018, 12:00 UTC (Data: EUMETSAT).

## Spatial Solar Potentials of Traffic Routes – PV2Go

In vehicle-integrated photovoltaics (VIPV), Fraunhofer ISE is conducting research on both the integration of PV into vehicle exteriors – as has been demonstrated impressively with a colored solar car roof – and the potentials of this type of integration for commuters, families and road freight transport. VIPV increases the range of vehicles with (hybrid) electric drive units and provides a partial power supply for electric systems on board, regardless of the type of drive unit. The irradiance and yield potential depend strongly on routes, times of day and utilization profiles.

Two projects that are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), "LadePV" and "PV2Go", complement each other ideally: Whereas "LadePV" investigates the commercial viability of PV applications in road freight transport, the focus of "PV2Go" is on investigating the solar potentials of German roads with irradiance measurements that address commuter and family vehicles. These data are to be compared to satellite-based irradiance data. We have developed an autonomous, solar-powered irradiance sensor which can transfer its position, irradiance and ambient temperature values via LTE once a second. In addition, it can buffer up to two weeks of the vehicle being in the garage, which is one reason for the sensor's size. The sensors that were developed in "PV2Go" are also used in the "LadePV" project.

One of the goals of "PV2Go" is to develop a spatial model of the solar potential of roads over the course of days and a year, taking the local shading by buildings, topography and land usage into account. The large amounts of data needed for this (solar irradiance, location of roads, digital surface models, LIDAR data, aerial photographs, classified satellite images e.g. for land usage) are drawn from public data sources and complemented by daily updated, almost real-time irradiance data from satellites. As part of a citizen science campaign, we will gather extensive data on irradiance with the help of interested citizens by mounting the sensors described above onto a large number of vehicles. To this purpose, Fraunhofer ISE will lend approximately 100 of such sensors for the duration of one year. The acquired data will serve to validate the solar potential model and additionally to obtain typical usage profiles in the transport sector.




Graph: Spatio-temporal irradiance maps over the terrain: irradiance as a function of position and time.

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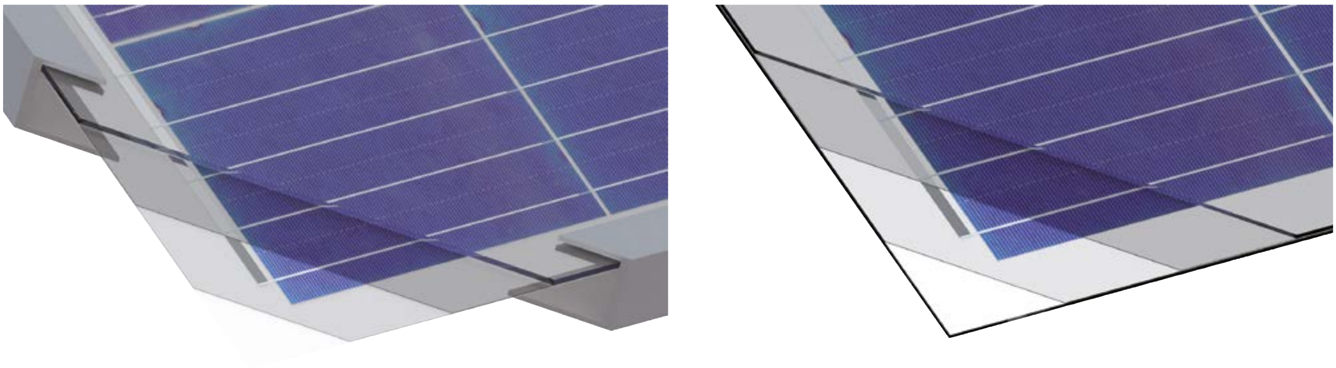
1 Location-tracked irradiance sensor for vehicles.



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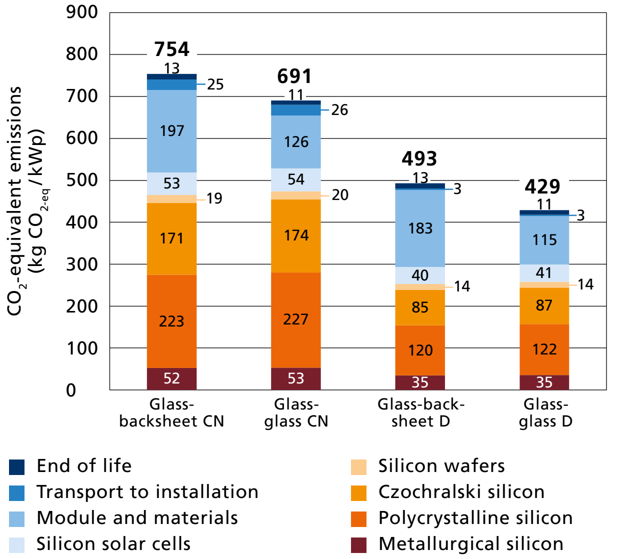
## Life Cycle Analysis of Modules: Glass-Backsheet Versus Glass-Glass

Photovoltaics is perceived as a "green" technology to supply energy from renewable sources, but its production affects the environment and resource consumption. A holistic evaluation is essential for the energy transformation. Therefore, we have investigated the environmental effects of solar modules over the complete life cycle from production up to recycling according to different categories (climate change, fine dust emission, water pollution, etc.). To evaluate the effects on climate change, we have determined the $CO_2$-equivalent emissions of solar modules over a period of 100 years according to IPCC 2013. We modelled the material and energy consumption for production over the entire value chain. The solar module considered here is based on silicon solar cells and has a nominal power rating of 330 W. Unlike previous studies, we have taken more recent developments such as diamond wire sawing for wafer manufacturing and current data for silicon, solar cell and module production into account. Production is not restricted to a single location: Intermediate products from metallurgical silicon to the module can be produced in different regions.

We have compared the complete value chain for production entirely in China with that for purely German production and applied the relevant current energy mix. As our study considers the most recent industrial data, our $CO_2$-equivalent emissions for solar modules are up to 75 % lower than in earlier studies. As can be seen in the graph, complete production in Germany would cause 35 % lower emissions than in China (493 kg compared to 754 kg $CO_2$-eq / kWp). The reason for this is simple: In China, electricity is predominantly generated from fossil fuels, with renewable energy having a share of 28 % in 2019, whereas the value in Germany was 46 %.




Graph: $CO_2$-equivalent emissions for c-Si solar modules, for different production locations and module designs, based on IPCC 2013.

Furthermore, we have compared glass-backsheet to frameless glass-glass modules. The latter cause even lower emissions. The results emphasize that high-performing and durable solar modules really do represent a particularly climate-neutral pillar for a future energy supply, that their production causes lower $CO_2$-equivalent emissions than previously known and that production entirely in Germany rather than China causes 35 % less $CO_2$-equivalent emissions. By applying glass-glass modules, the emissions can be reduced even further.

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1 CAD drawings of a glass-backsheet module with an aluminium frame (left) and a frameless glass-glass module (right).

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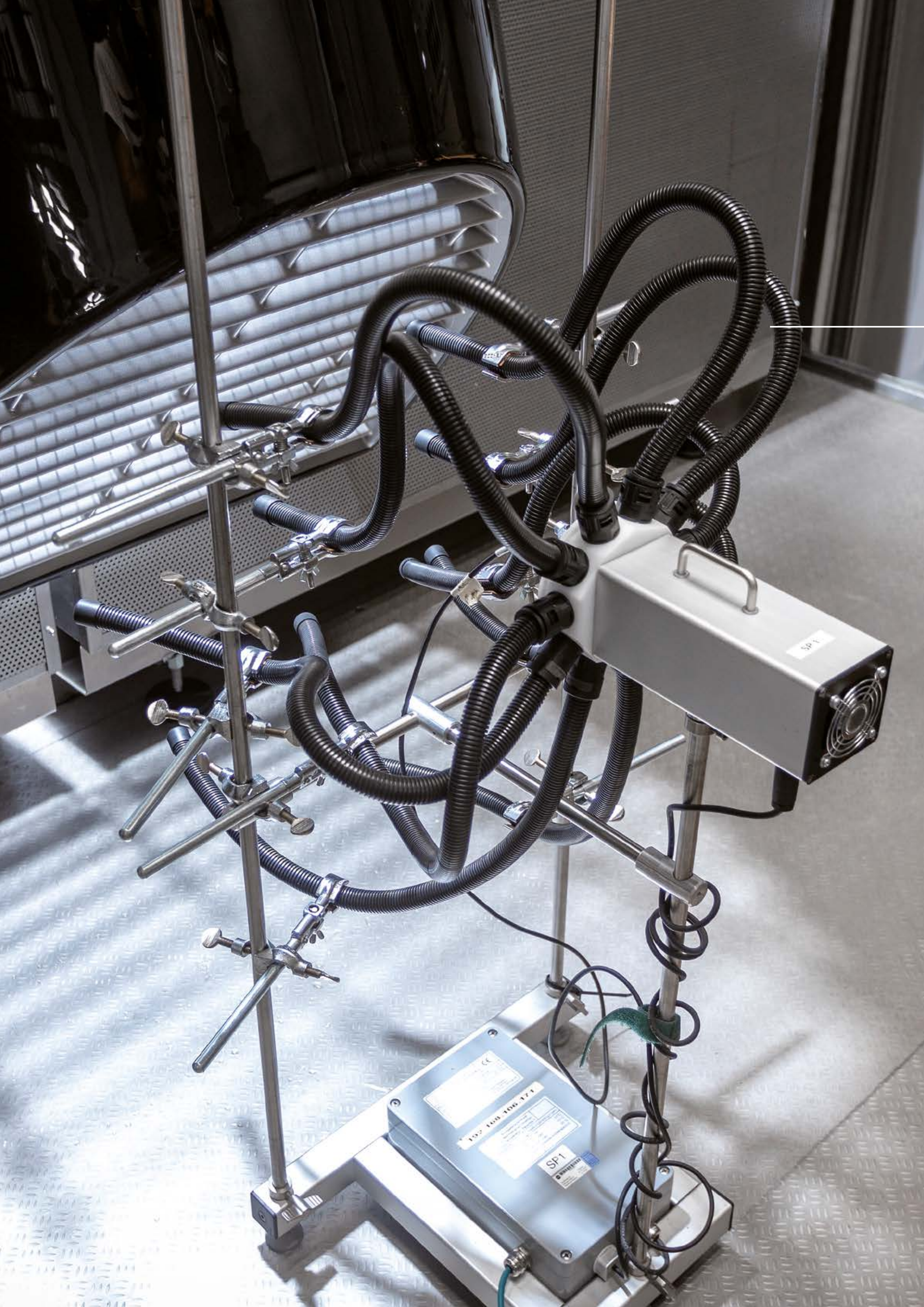
## Selected Projects in 2020

- 50Prozent / 50Percent – Monolithic III-V Multi-Junction Solar Cells with More than 50 % Efficiency under Concentrated Irradiation
- APV Obstbau (Orcharding) – Agrivoltaics as Resilience Concept for Adaptation to Climate Change in Orcharding
- micro-CPV – Development of a Highly Concentrating CPV Module Based on Modern Micro-Production Technology
- APV-MaGa – Agrivoltaics for Mali and Gambia: Sustainable Electricity Production by Integrated Food, Energy and Water Systems
- PV$^2$WP – PV Prediction for Grid-Compatible Control of Heat Pumps
- PV-Süd – PV Roofing Over Roads
- PVwins – Development of Wall-Integrated PV Elements for Noise Protection
- RoMoT – Robust Module Technology for High Solar Irradiance

More information on these and further projects:
www.ise.fraunhofer.de/en/research-projects/1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# Energy Technologies and Systems

Storage as well as the efficient transformation, distribution and utilization of energy play an equally important role for a successful energy transformation as processes to collect energy. Fraunhofer ISE has been addressing research and development topics in this spectrum for 40 years – as a broadly based, single Institute, but also in cooperation with other institutions. A current example is the Fraunhofer Cluster of Excellence for "Integrated Energy Systems" CINES, an association of four Fraunhofer Institutes, for which the Institute Director, Prof. Hans-Martin Henning is the speaker. CINES recently presented 13 theses to demonstrate how our energy system could develop up to the middle of this century, based on renewable energy as the most important source of energy. According to this scenario, the end energy demand for fossil fuels will indeed decrease but the electricity consumption for transport, heat in buildings and industrial processes will increase markedly due to sector integration. In order to reach the climate change goals, certain key technologies thus hold central importance. Fraunhofer ISE identified these in the study "Paths to a Climate-Neutral Energy System", and quantified their significance in different scenarios. As not only technical feasibility and costs but also social behavior play a decisive role, it is important to transfer scientific insights and solutions with broadly based communication and discussion, thus contributing to understanding, acceptance and social participation.

Heat pumps represent one of the required key technologies in the heating sector that not only can apply electricity for space heating and domestic hot water in buildings but also supply industry with process heat. Fraunhofer ISE has made this topic one of its research priorities, particularly to advance the utilization of climate-friendly refrigerants and optimize the costs and efficiency of the systems.

The importance of chemical and electrical storage is also growing dramatically. Hydrogen will be very significant for the mobility sector in various ways – via fuel-cell drive units or synthetic fuels. Fraunhofer can contribute experience from 30 years of research on fuel cells to upscale fuel cell production in Germany, among other aspects. Industrial processes and the production of liquid fuels represent further applications of hydrogen with strong potential for growth. We address the development of processes both to reduce costs for PEM electrolysis and also to produce methanol and other fuels on the basis of hydrocarbons. In order to advance the production of batteries in Germany – which is decisive not only for electromobility – the Research Fab Battery Cells (FFB) in Münster is working on optimizing materials and processing technology, production technology, digitalization and economic viability. Fraunhofer ISE is contributing with its expertise to quality control of the individual process steps and the forming of battery cells.

Digitalization plays a major role in increasing the flexibility and stability of electricity grids. With the new Digital Grid Lab in our Center for Power Electronics and Sustainable Grids, we intend to further expand our research activities in this field. In order to monitor electricity generation constantly and provide transparency regarding the electricity supply and costs, Fraunhofer ISE has been issuing the Energy Charts since 2014. These have now been extended to include other European countries and new functionality. The interested public was able to observe that the share of renewable energy in the German electricity grid achieved a new record value of about 50 % in 2020.

**Photo: Measurement of the air temperature and humidity at the outlet of an outdoor heat pump.**

# Heat Pumps – A Key Technology for the Energy Transformation

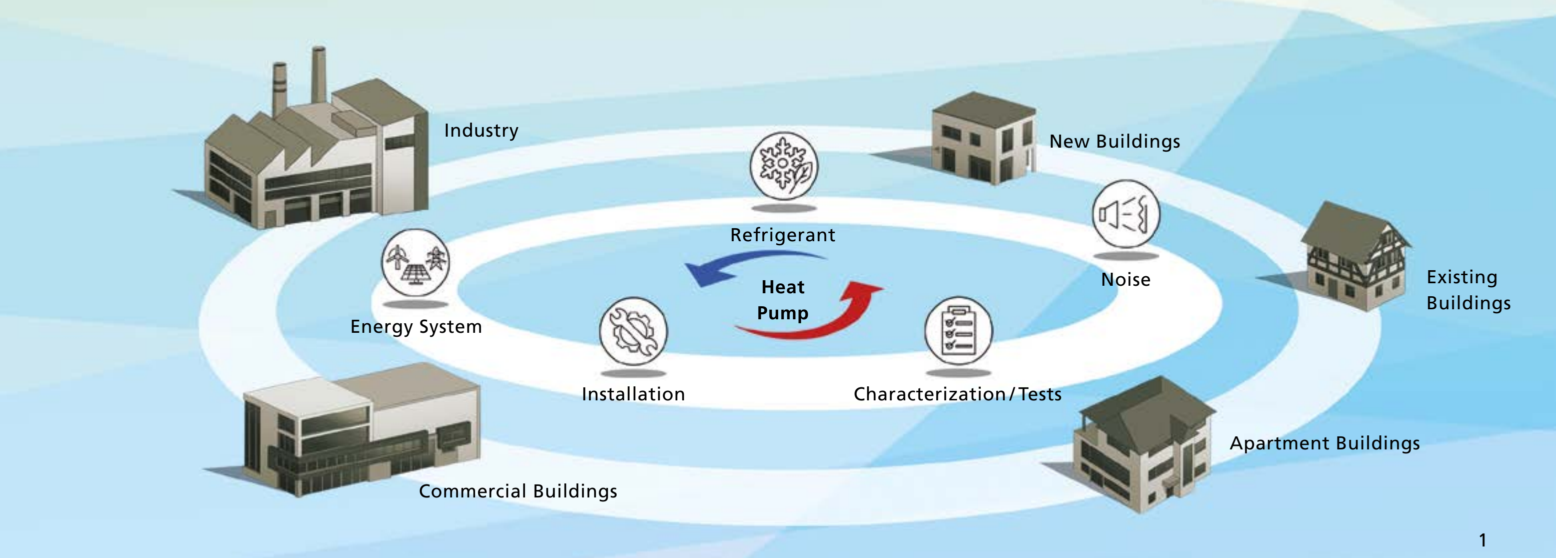
Numerous scientific studies have concluded that heat pumps will be the dominating heating technology in future energy systems. For many years, they were primarily considered to be a solution for new, free-standing houses. Meanwhile, however, it has become clear that the technical application opportunities are much more diverse: new buildings, existing buildings, refurbished houses and apartment blocks, non-residential buildings and whole neighborhoods can be supplied with heat and cooling energy on this basis, efficiently and reliably. The building sector, where providing heat is responsible for around 19 % of the $CO_2$ emissions in Germany, could achieve climate neutrality in the long term through the widespread application of this technology.

Heat pumps are commercially available with capacities up to the two-digit megawatt range. High-temperature heat pumps are already applied in industrial processes with temperatures up to 160 °C. They tap different sources of ambient heat (outdoor air, the ground, groundwater, wastewater, solar thermal systems). Decarbonizing and electrifying the heat supply with heat pumps not only makes it feasible to use renewable energy efficiently but also makes electricity consumption more flexible – particularly if heat storage is included – and thus stabilizes the electricity grid.

The importance of heat pumps for the energy transformation is accompanied by challenges for the equipment manufacturers. Methods, components and products must be developed, integrated and established. In addition, the rapid market growth also demands efficient, cost-effective production methods to remain competitive. Further optimization is needed to simplify the installation of heat pumps in various application areas and to increase operating efficiency. As a key technology for the energy transformation, heat pumps thus represent a key topic for Fraunhofer ISE, in which we combine existing competences and expand capacity. We are working on various technological questions to optimize materials, components and equipment and thus provide competent support to our partners.

**Utilizing Natural Refrigerants**

Refrigerants circulate as working medium in cooling circuits and transport heat from the cold to the hot side of the process. The choice of refrigerant essentially determines the efficiency which can be reached in the cooling circuit of heat pumps and technical cooling applications. However, the refrigerants differ strongly with respect to their climate change effect, toxicity and flammability. The F-gas regulation of the European Union prescribes the stepwise reduction of fluorinated greenhouse gases used as refrigerants. This has resulted in new developments or conversion by manufacturers of equipment and devices throughout the world. Fraunhofer ISE concentrates particularly on sustainable, efficient and long-term solutions with natural refrigerants such as propane. Within the project "LC150 – Development of a Refrigerant-reduced Heat Pump Module with Propane", which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and started in October 2020, we are developing a compact and cost-effective cooling circuit. The development work is supported financially and advised technically by a broad industrial consortium of European heat pump manufacturers. Beyond this, we work on safety concepts and tests for heat pumps.




**Reducing Noise Emission**

Most building heat pumps use air as their heat source: Ambient air is drawn in, directed through a heat exchanger and cooled thereby. The heat is accepted in the cooling circuit of the heat pump. Noise can be caused by the air current, the fan and the compressor of the heat pump. This is emitted through the air and the equipment housing to the environment to a greater or lesser degree, depending on the type and location of the installation. Depending on the location and the operating point, this noise can be disturbing. As the number of heat pumps installed outdoors near buildings increases, the demands on the equipment acoustics also increase, particularly in densely populated urban areas. Work at Fraunhofer ISE is concentrating on the development of simplified procedures to identify noise sources and the acoustic and structural dynamic evaluation of components (e.g., compressors) and devices.

**Ensuring Equipment Quality**

Hybridization of equipment, innovative control concepts and smart integration into the energy system lead to increasingly complex heat pumps. As a result, device and system measurement under controlled conditions during both product development and the evaluation of equipment and technology is becoming increasingly important. In the TestLab Heat Pumps and Chillers, Fraunhofer ISE carries out accredited measurements for almost all product groups. We also support our clients during the development process with innovative testing and evaluation methods, providing information on the product behavior under different operating conditions. To this purpose, we carry out hardware-in-the-loop tests. Our partners can thus significantly reduce the time between an initial idea and product commercialization.

**Optimizing Installation and Operation**

The next significant development step is to increase the ecological and economic efficiency of the whole system. Attention is thus directed to the installation and operating phases. We develop methods for digitally assisted quality control during installation and use artificial intelligence methods to optimize the operating phase. This should enable not only faster installation of the heat pump systems on-site with minimal errors but also self-optimization and monitoring in operation.

**Integrating into the Energy System**

A core element of the energy transformation is sector integration, particularly direct and indirect use of electricity from renewable sources in all consumption sectors. Heat pumps must be integrated intelligently into the energy system so that they can be used to make electricity consumption more flexible and thus stabilize the electricity grids. Intelligent controls and operation management systems are needed. New business models will arise for utilities, grid operators and system owners. At Fraunhofer ISE, we develop and test tools and concepts for optimal integration of heat pumps into the electricity system of the future.

1 Heat pumps will be the dominant heating technology in the future energy system. They are already used in many types of buildings today.

# Energy-Efficient Buildings

The energy efficiency of buildings plays a central role for the energy transformation: More than 40 % of the end energy demand in Germany is caused by the building sector. To achieve climate-friendly building operation, we must reduce the energy demand and then meet it with renewable energy sources to the greatest extent possible. The research work of Fraunhofer ISE addresses nearly all phases in the life of a building – from planning through construction to operation.

We work on reducing the demand for space heating and space cooling with optimized building envelopes and by integrating 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. Examples can be found in a database with extensive data and tools to construct nearly-zero energy buildings.

For supplying heat to buildings, we concentrate mainly on heat pumps. Our work on this technology addresses the entire value chain: from component development for the cooling circuit, through equipment and systems development, to quality assurance in practical operation. Funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and involving a broad industrial consortium, we began with the development of a compact propane cooling circuit in October, 2020.

The digitalization of processes is also an important component to increase energy efficiency and promote sector integration. 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. Product data form an important part of these data-based processes. In July 2020, we became the European Regional Data Aggregator for the National Fenestration Rating Council NFRC and contact for European glazing manufacturers who address the North American market with their products.

150
Total staff

24
Journal articles and contributions to books

42
Lectures and conference papers

4
Newly granted patents

Our newsletter offers regular updates on our research milestones.

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

Photo: Administration center of the City of Freiburg with façade-integrated photovoltaics.

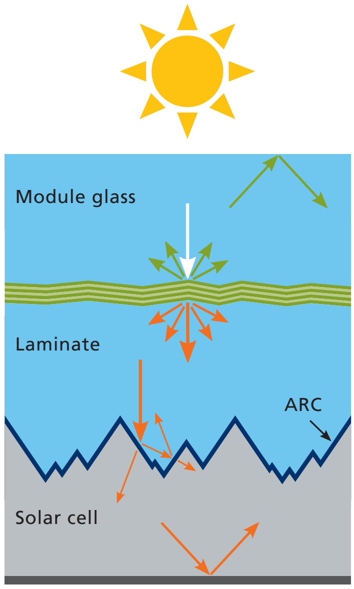


## MorphoColor®: Aesthetically Attractive PV Modules and Solar Collectors

The integration of photovoltaic modules and solar thermal collectors into buildings and vehicles makes the use of large areas feasible for collecting renewable energy. In these applications, aesthetic aspects are decisive for their acceptance. The architectural design must be able to determine the color. Many architects, but also car designers want "attractive" modules which offer a homogeneous and freely selectable color impression with saturated colors that do not vary with the viewing angle and have a minimal effect on the module's electrical efficiency. However, previous concepts were very limited in the choice of colors, they were very angle-dependent, caused large losses in efficiency or were not suited for industrial production.

At Fraunhofer ISE, we solved this problem by applying the MorphoColor® effect, named after the morpho butterfly, to achieve an angle-invariant and saturated color impression. It is a bionic concept that is based on complex three-dimensional photonic structures.

The angle-invariant color effect arises due to the interaction of geometrical structures and interference films, which we deposit onto the internal surface of the glass cover to the module or collector. In this way, the existing production process for the solar cell or the solar thermal absorber remains unchanged; it is only a separate glass cover that is used. To describe the optics of this system efficiently, which consists of thin films in the nanometer region, surface structures on the order of micrometers and glass panes of several millimeters thickness, use was made of the 3D modelling algorithm "OPTOS", which was developed at Fraunhofer ISE.




Graph: MorphoColor® coating on the inner surface of the module glass cover, including the relevant scattering and refraction phenomena.

Based on this simulation, we define the requirements for the surface structure and the interference layers. Its special implementation ensures high color saturation and simultaneously high output power equaling more than 90 % of that for the original black modules or collectors. These high efficiencies have already been demonstrated over areas of 1 m × 1 m. To illustrate the wide range of design options, we have produced a palette with more than twenty colors. The colored glass covers for modules and collectors are produced cost-effectively by applying sputter-coating processes that are industrially available for large areas.

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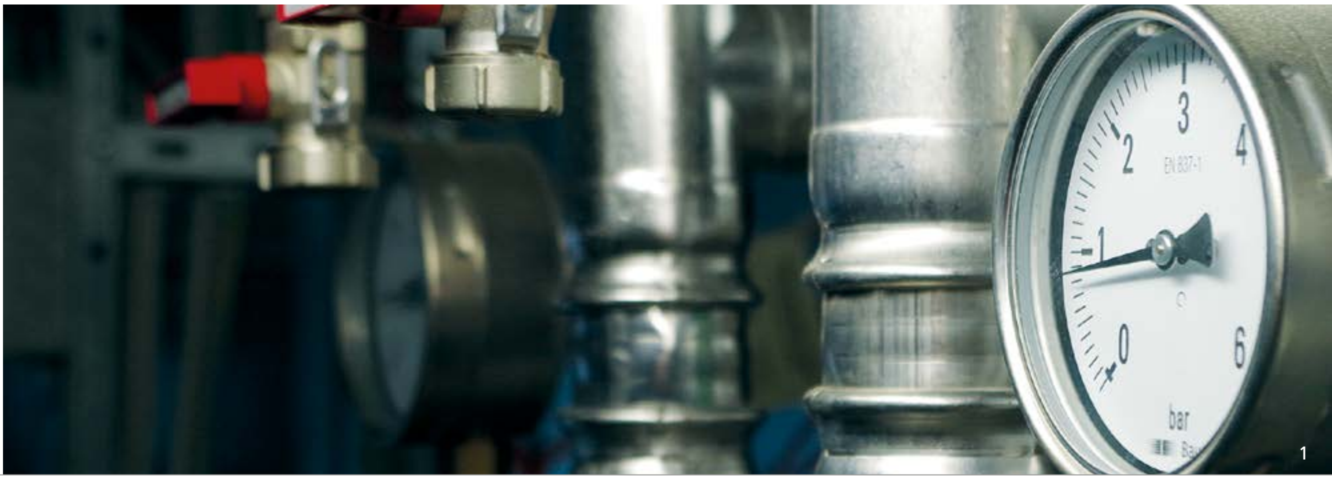
1 MorphoColor® PV modules of 1 × 1 $m^2$ area. A module efficiency of 93 % with respect to the black reference module was achieved.

2 Palette of the currently available MorphoColor® coating colors.




## Description of Building Automation in BIM

Building automation systems have integrated increasingly more functions over the past decades, such as controlling heating, air-conditioning, ventilation, lighting and fire safety. They ensure that buildings are operated in a energy-efficient, comfortable and safe manner. However, in most buildings, information on the control functions implemented in the automation systems is poorly documented or difficult to access and thus cannot be evaluated. The reason is the lack of uniform digital schemata to describe them.

Within the “EnergieDigital” project, that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE has developed a method based on Building Information Modelling (BIM) to describe the functions of building automation systems digitally and to make them accessible to many different actors during the entire lifetime of building automation systems. The method adopts the principles of widespread guidelines such as VDI Guideline 3814 to describe control functions. Its core is a combination of ontology-based descriptions of the control system topology, i.e. a digital schema of the relationships between sensors, actuators and controllers, and a model of the control functions to be implemented. These are based on the IEC 61131-3 standard, which represents the foundation for programmable logic controllers (PLC).

To describe the sensors, actuators and controllers, we used three already existing ontologies: SEAS (Smart Energy Aware Systems), SOSA (Sensor, Observation, Sample and Actuator) and CTRLont. As it is not very practicable to describe the control mechanisms with Semantic Web Technologies, we did not store the actual logic of the controls as an ontology but implemented it directly as program code with the OpenPLC editor and linked this with the ontology. In this way, a framework is created that allows information on control functions to be acquired in a consistent digital representation and to be used for the planning, projection and operation of building automation systems.

We have already demonstrated the method in the laboratory and will implement and validate it in 2021 within the lighthouse project in the “Viega World” training center in Attendorn.

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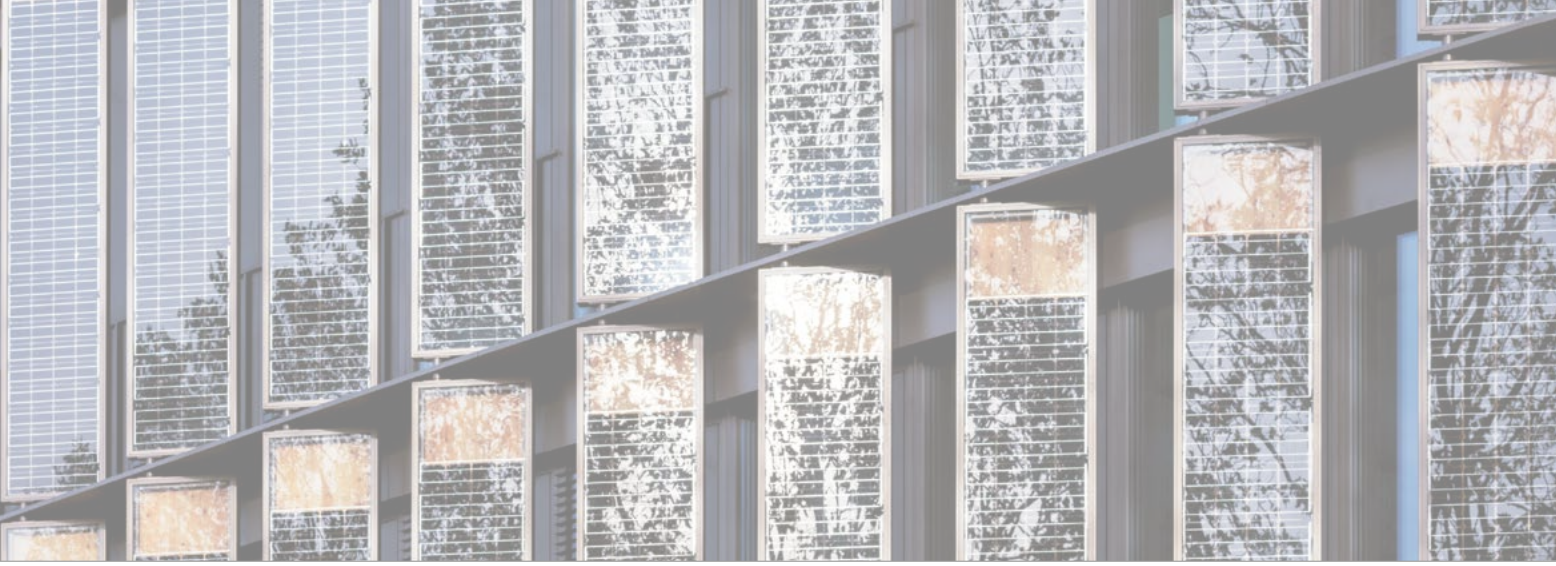
1 Heat distribution and measurement systems of an air-conditioning system.



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## Selected Projects in 2020

- integraTE – Initiative for Market Establishment and Dissemination of Thermal-Electrical Energy Supply Systems with PVT Collectors and Heat Pumps in the Building Sector
- Copernicus-Ariadne – Evidence-Based Assessment to Map Out the German Energy Transformation
- ICON LBNL-Fraunhofer ISE – Models and Methods for Optical and Thermal Characterization of Building Envelopes
- LowEx-Bestand-HTWP – Cooperative Project on LowEx Concepts for the Heat Supply of Retrofitted Existing Multi-Family Buildings
- LowEx-Bestand NK4HTWP – New Refrigerants for High-Temperature Heat Pumps
- safeSENSE – Development and Evaluation of an Innovative Safety Feature for Heat Pumps with Natural Refrigerants Based on Sorption Elements and Novel Sensor Technology
- WAMS – Heat Pumps – Acoustics and Multi-Source Systems

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

# Solar Thermal Power Plants and Industrial Processes

In sunny regions, solar thermal power plants based on Concentrated Solar Power (CSP) and equipped with large thermal storage units provide dispatchable electricity. Together with our partners, we are conducting research to further improve materials, coatings, components, collectors and systems, so that efficiency is increased and manufacturing costs are reduced. Thus, in 2020, Fraunhofer ISE presented a calibration and control system for heliostat arrays based on digital image processing. It allows the focal spot positions of many heliostats to be determined during operation, in real time and cost-effectively, for the first time. We also optimize the quality and lifetime of components and have developed new reflector coatings for secondary reflectors in power towers, for example.

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 processing heat into the heat supply for industrial processes. We have developed a publicly accessible online tool for rapid techno-economic evaluation and presented it in workshops.

The efficient conversion and transfer of heat is another focus of our work. We conduct research on the materials and components needed for efficient heat exchange. Questions of humidification and dehumidification form the link to our work on water treatment. Under commission to a Chilean mining company, we set up a processing sequence to separate solar salt from Chilean salpeter sols on a technical demonstration scale and demonstrated its continuous operation.

Fraunhofer ISE possesses profound expertise in materials science, component design, characterization and testing procedures, 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.

57
Total staff

8
Journal articles and contributions to books

4
Lectures and conference papers

3
Newly granted patents

Our newsletter offers regular updates on our research milestones.

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

Photo: We work on resource-conserving processes to produce salts in South America.

## Optimized Filler Materials for High-Temperature Storage

The integration of efficient thermal energy storage makes previously unused industrial waste heat usable. Operating high-temperature heat storage tanks more efficiently and cost-effectively in the future is thus an essential goal of the "FENOPTHES" research project that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). Under the coordination of Fraunhofer ISE, filler materials are developed in this project that should replace conventional storage fluids to a large extent. We are investigating different material combinations and geometrical forms. Based on the insights gained, a demonstrator unit will be integrated at the site of one of our industrial partners in a later phase and tested in operation for its reliability and efficiency. In a first step, we have determined the waste heat potential on-site by mounting sensors in the chimneys.

Suitable filler materials must meet many criteria: Good heat transfer to the fluid, high thermal conductivity within the filler material and a high heat capacity to reach high storage density are decisive characteristics. In addition, compatibility with the working fluid of the storage unit and stable material properties over a long service life are required. Furthermore, both the materials and their production should be environmentally friendly and inexpensive. In testing the thermal properties of different filler configurations, we pursue a new concept: The filler configurations are initially evaluated, not in high-temperature media like thermal oil or molten salt, but rather in water in a dedicated test stand. To this purpose, we were able to use the well-suited infrastructure of the TestLab Heat Pumps and Chillers at Fraunhofer ISE. We successfully measured the first filler configurations.

Compatibility with the high-temperature media was investigated separately in long-term experiments. In order to differentiate between effects that may arise, the working fluid and filler are thermally cycled both separately and in contact with each other. Chemical analyses and mechanical load tests subsequently determine their suitability. Compatibility tests are currently being run with molten salt for the application of fillers in the storage tanks of solar thermal power plants. After adaptation of the molten-salt test infrastructure at Fraunhofer ISE, the most promising filler candidates will be tested in operation with molten salt in a laboratory-scale storage prototype to verify the previous investigations. The described experiments also serve to validate numerical models which we use to represent storage behavior, for tank design and for system simulations. With these models, we are able to simulate and optimize the intermediate storage and subsequent usage of the waste heat in the industrial demonstrator.

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1 Filling the crucibles with fillers and high-temperature media for compatibility testing.

2 The prepared crucibles are thermally cycled in a high-temperature furnace.


## Automated Soiling Measurements in Solar Thermal Power Plants

The soiling of reflectors or absorber elements in solar thermal power plants depends strongly on the location and can even vary significantly across the site of a single power plant. The nature of the land surface and soil, meteorological conditions and natural and anthropogenic emissions in the surrounding area all play a decisive role and can lead to appreciable uncertainty regarding yield prediction and cleaning costs in operation. This uncertainty also increases the financing costs. Better understanding of the soiling characteristics and rates is thus important for choosing the right location and for the economically viable operation of solar power plants.

In the "AVUSpro" project that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE is investigating and optimizing solutions to this problem, taking soiling and corrosion effects into account. To this end, we are developing three measurement methods to characterize the soiling of the power plant components and thus improve the basis for yield prediction.

The prototype of the "AVUS" measurement instrument, which was developed in the project, allows the soiling to be measured automatically, e.g. at hourly intervals. The data are analysed together with the meteorological data from the local measurement stations or within the power plant itself. Further development of the "AVUS" instrument will ensure increased reliability during automatic operation.

The portable "pFlex" reflectometer, which was also developed at Fraunhofer ISE, is suited for quick manual measurements at the solar field and offers advantages compared to existing systems. The most important technical development is its extended functionality via a data evaluation app.

Furthermore, in the future it will be possible to monitor the large-area soiling on thousands of solar reflectors from a vehicle or a drone using the camera-based method, "FREDA", and thus detect defects on the reflectors.

Accompanying laboratory investigations with the "VLABS" instrument also revealed new information regarding the scattering and absorption of solar radiation by dust and soiling. It became evident that the reduction in reflected radiation depends strongly on the angle of incidence.

The methods named above demonstrate that a much more reliable yield prediction is possible by combining them with physical models. Our research activities also contribute to optimizing the cleaning concepts during operation of a power station. This increases the yield and simultaneously minimizes water consumption, which in turn reduces the operating costs.

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1 AVUS instruments (left) at the test stand of Fraunhofer ISE in Freiburg-Hochdorf. Comparative measurements with PV soiling instruments.

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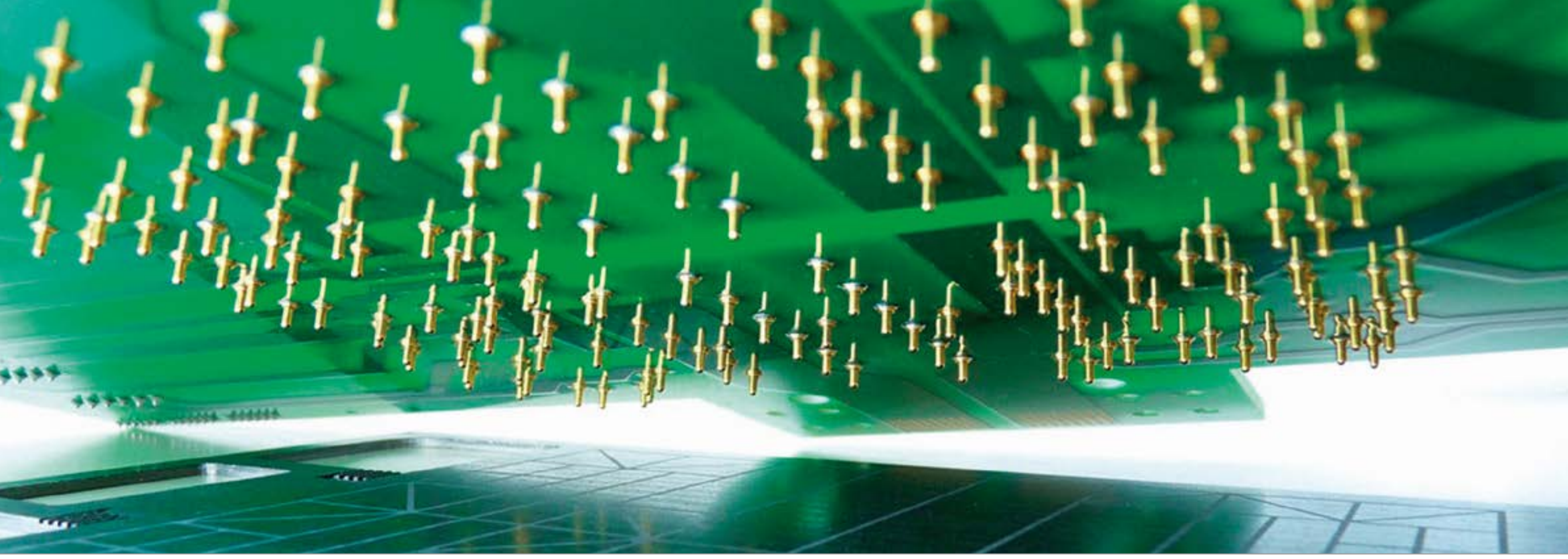
## Selected Projects in 2020

- Jumbotrough – Development of a Robust Large-Format Parabolic Trough Reflector
- CAS-T – Software Development for Solar Tower Plant Design and Optimization
- Solar Thermal Power Plants for the Power Systems in the MENA Region – Power Plant Analysis and Integration into the Power Markets as Part of MENA CSP
- SFERA-III – Solar Facilities for the European Research Area – Third Phase
- SubSie Platform – Sorption Steamers for Vessel Temperatures Less 0 °C
- Polyphem – Small-Scale Solar Thermal Combined Cycle (Gas Turbine / ORC)
- INSHIP – Integrating National Research Agendas on Solar Heat for Industrial Processes
- SEArcularMINE – Extracting Raw Materials From Concentrated Sea Water

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



# Hydrogen Technologies and Electrical Energy Storage

**Hydrogen Technologies**
We conduct research on the production, conversion and further thermo-chemical processing of hydrogen. In the context of the increasing importance of green hydrogen as a fuel, we led the work on the Fraunhofer Hydrogen Roadmap last year and surveyed the potential in our region within the project "H2-SO – Hydrogen Technologies in the Southern Upper Rhine". With regard to hydrogen production, we are concentrating on polymer-electrolyte membrane electrolysis (PEM). We also apply PEM technology to develop fuel cell systems, particularly for the mobility sector. In the "HyFab" project, we are investigating automated production and quality control processes for the industrial production of fuel cells. Based on thermo-chemical processes, we synthesize liquid fuels and chemicals from hydrogen and carbon dioxide (power-to-liquids). One example is our new miniature plant for methanol synthesis.

**Electrical Energy Storage**
For battery materials, cells, modules and systems, we investigate new material combinations, cell architecture and manufacturing processes, construction and interconnection technology, formation, aging and characterization. We are participating in the project "Research Fab Battery Cells" (FFB), which aims to expand German battery research and is funded by the German Federal Ministry for Education and Research (BMBF). Accreditation of our battery testing laboratory by DAkkS (Deutsche Akkreditierungsstelle) is planned for 2021. The laboratory is part of the "Development and test center for batteries and energy storage systems" in the Haidhaus in Freiburg, which is supported by the State Ministry for Economics, Labor and Housing in Baden-Württemberg and the BMBF. We also develop complete prototypes and accompany our partners 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, covering the whole range up to the electrification or hybridization of ships.

176
Total staff

13
Journal articles and contributions to books

10
Lectures and conference papers

2
Newly granted patents

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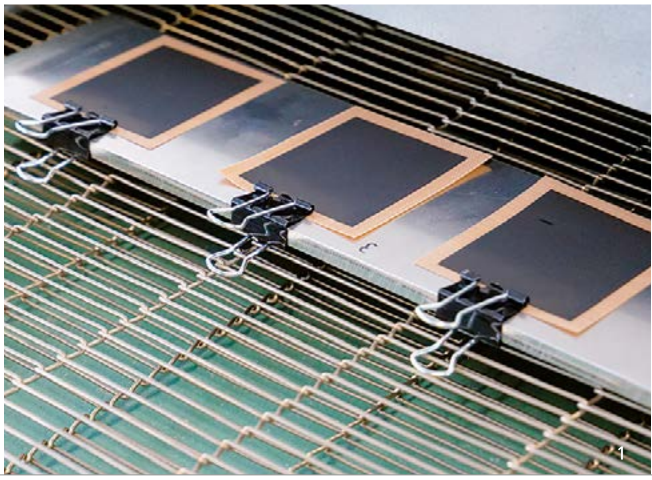
Photo: A current-conductor plate contacts a segmented gas flow-plate of graphite.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## Screen Printing to Produce Fuel Cell Electrodes

Within the "DEKADE" project that is funded by the German Federal Ministry for Education and Research (BMBF), Fraunhofer ISE has developed flatbed screen-printing as a manufacturing process for fuel cell electrodes, which can be scaled up to industrial dimensions. To this purpose, we combined our competence in production and fuel cell technologies.

A production process applying flatbed screen-printing offers advantages compared to the conventional, continuous roll-to-roll process for structuring electrodes. The proton-conducting binder polymer (ionomer) plays a special role for structuring in the "through-plane" direction. For low current densities, high proportions of ionomer are desirable, as protonic resistance has a greater limiting effect than oxygen diffusion resistance. For high current densities, the situation is reversed. As the reaction zone moves away from the membrane when the current density increases, an ionomer gradient in this direction is advantageous. This approach was implemented in the "DEKADE" project with multi-layer screen printing. Compared to homogeneous electrodes, the power density of the investigated fuel cells at 0.6 V was increased by approximately 10 %. Accompanying modelling work confirmed the underlying effects which led to the power increase. In other current projects, we are also investigating the techno-economic aspects of fuel cell production by flatbed screen-printing.

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## Standardized Measurements in PEM Water Electrolysis

The German National Hydrogen Strategy has focused public attention on the production of green hydrogen as an important driver for the energy transformation. Producing green hydrogen by PEM electrolysis with the help of electricity from renewable sources is a particularly promising approach. To achieve the targeted power densities, it is essential to further develop both the technology and the applied materials.

However, the results from different research groups are not always directly comparable to each other due to the diverse effects of the different cell components and materials. For this reason, Fraunhofer ISE is working within the framework of the International Energy Agency (IEA) to develop standardized measurement equipment and harmonized test protocols.

One of the electrolysis cells that we developed, with an active area of 4 $cm^2$, has developed into an international reference cell due to its robust configuration and easy handling. By using reference materials and a mutually agreed measurement protocol, which includes all important input parameters such as conditioning, temperature, pressure of the product gases, water flow rate through the cell and clamping pressure on the active area, the results measured by different research groups showed a very good agreement.

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1 Fuel cell electrodes on transfer films during the drying process. In the next step, these are laminated onto a membrane and then form the heart of the fuel cell.

2 Reference test cell with device for controlled application of clamping pressure. In the foreground are two half-cells with a parallel flow field.

## High-Resolution Measurement Technology Offers New Insights into Methanol Synthesis

With more than 100 million tonnes being produced annually, methanol is one of the chemicals that are produced in the largest quantities globally. Today, almost exclusively fossil resources are used as raw materials, and 0.5 to 0.77 tonnes of $CO_2$ equivalent are emitted per tonne of methanol. By contrast, a methanol synthesis based on electrolytic hydrogen from sustainable energy and $CO_2$ makes a technical carbon cycle and coupling of the energy, chemical and transport sectors feasible. Fraunhofer ISE is investigating this synthesis in a mini-plant, which was planned, built and taken into operation in 2019 within the "Power-to-Methanol" project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

The plant, which was conceived for highly dynamic operation, converts hydrogen and $CO_2$ into methanol in a continuous process. There are still various hurdles to be overcome to upscale this process for major industrial implementation. For example, high $CO_2$ fractions in the synthesis gas cause accelerated aging of the catalyst. We can investigate this and other aspects – also for other reactions – in the miniplant. In addition, parallel modelling allows the results to be transferred quickly and efficiently to industrial plants.

In order to validate our own modelling approaches or those from the literature, a measurement and analysis system with high temporal and spatial resolution was installed in the miniplant. The combination of infrared spectroscopy (FTIR) for product analysis and a fiber-optical temperature measurement acquires real-time data about the processes occurring in the reactor.

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1 Miniplant at Fraunhofer ISE.

## Ammonia as a Platform Molecule for Sector Coupling

During the population growth of the 19th century, the phrase "bread from air" became established – a challenge to science which found its conclusion in the Haber-Bosch process to synthesize ammonia. Today's analogy is hydrogen from renewable energy, providing the key to a sustainable energy system. Ammonia as a sustainable, hydrogen-based fuel and link between different sectors, is at the focus of attention in this context.

A recent study by Fraunhofer ISE on Power-to-X (PtX) value chains reveals that ammonia has various advantages compared to other PtX products, such as economic appeal, low $CO_2$ avoidance costs, very low transport costs due to a high energy density, great flexibility in the choice of production location as only air, (salt-)water and renewable energy are needed as inputs, and finally the potential to address different applications in the chemical, industrial, energy and particularly maritime economic sectors. A modern ammonia synthesis offers new opportunities concerning the total process efficiency, manufacturing costs and sustainability. We are exploring this potential together with our Japanese partner, the National Institute of Advanced Industrial Science and Technology (AIST). We are focusing on the application of second generation catalysts in combination with innovative process intensification technologies. Our goal is a customized ammonia synthesis with higher yields per time and volume, taking dynamic operation into account.

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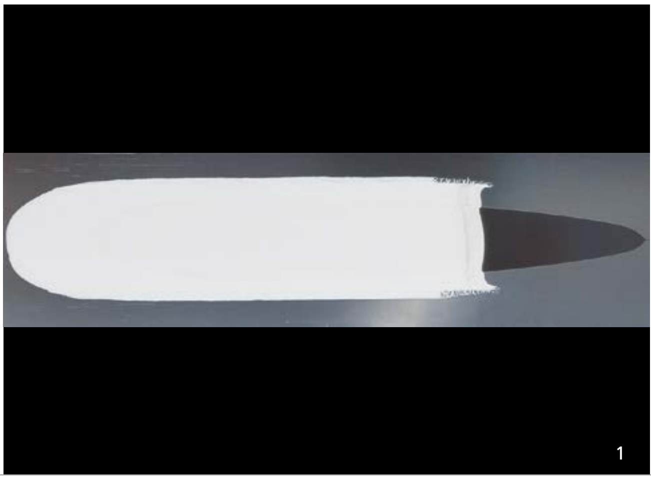
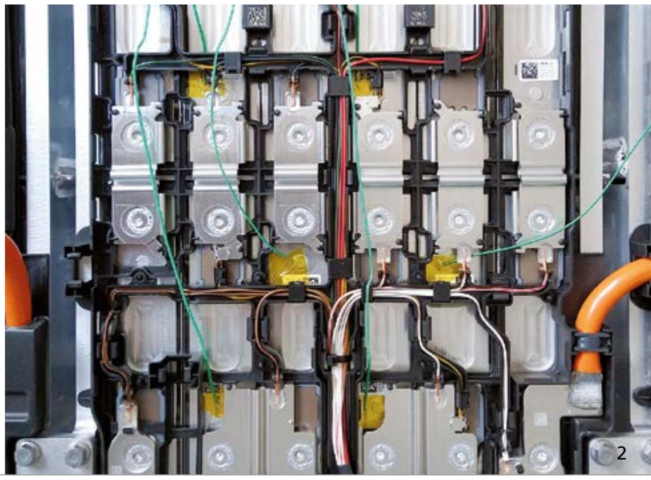
2 3D CAD drawing of the KISS facility for powder and particle kinetic investigations, where advanced catalysts for ammonia synthesis are investigated.





## Printed Lithium Solid-State Batteries with Sulfide-Based Ion Conductors

So-called "all solid-state" batteries possess solid ion conductors, which allow the thermal runaway of conventional battery cells with liquid electrolytes to be avoided. Furthermore, they simplify the application of metallic lithium as an anode, which should lead to a significant increase in the energy density.

In the "Printsolid" project that is funded by the Vector-Stiftung, Fraunhofer ISE is developing printing processes for such solid-state batteries with sulfide-based solid electrolytes. We have succeeded in producing a battery cell in which both the cathode and also the ion-conducting separator layer between the cathode and the anode can be printed (Fig. 1). The battery cell reaches more than 1000 charging / discharging cycles with relatively high charging (1 C, corresponding to one charge per hour) and discharging (C / 2, corresponding to one discharge in two hours) currents for a solid-state battery. After 1000 cycles, 80 % of the original discharging capacity was still available. This type of solid-state battery is of great interest for consumer electronics but above all for electromobility.

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## 2nd-Life Car Batteries in Stationary Applications

The expansion of electromobility makes a significant contribution to reducing the emission of pollutants and greenhouse gases. However, the production of car batteries is still very energy-intensive, so that the advantages of electromobility are realized only with a long service life. At the end of a reasonable service life in a vehicle, batteries can be used in a second application for stationary electricity storage. Their $CO_2$ balance improves due to the longer resulting total service life.

In the "EMILAS" project that is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), batteries are tested for their 2nd-life application as stationary buffer storage units in apartment blocks. We read out the operating data that were recorded during their first operation phase, including the operating duration in different power classes and state-of-charge ranges, as well as operation in different temperature classes. In addition, with the cooling deactivated, we investigated the suitability of the batteries for stationary application and determined the thermal switch-off limit of the battery management for high discharging currents. For the initial control, the batteries were subjected to capacity tests and pulsed tests in a test stand specifically programmed for this purpose, in order to determine their state of health. All investigated batteries were found to be suitable for further use. We are currently developing a thirty-minute quick test based on the processes for initial control and quality checks.

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1 Aluminium current collector foil with a printed cathode (right, black) and a separator layer (left, white) printed on top of it.

2 Characterization of a used car battery in the Fraunhofer ISE laboratory.


## "Haid-Power": Active Grid Relief by Commercial PV-Battery Storage

The ongoing electrification of the transport sector is accompanied by an appreciable transformation of the electricity sector and presents another major challenge to the German electricity grid – in addition to the expansion of electricity generated from fluctuating renewable energy sources. Far-reaching changes concerning the grid load can be expected particularly in the distribution grids as sector integration proceeds. In the "Haid-Power" project, which is funded by the State Ministry for Economics, Labor and Housing in Baden-Württemberg, Fraunhofer ISE is preparing solutions for these problems and testing them in practice.

In our new Development and Test Center for Batteries and Energy Storage Systems, we are developing a load and energy management system with intelligent peak load capping and combining it with a large photovoltaic installation and a hybrid battery storage unit. The goal is to avoid cost-intensive expansion of the existing distribution grid structure and simultaneously guarantee that the Center can operate. Within the project, it is possible to prove under real operating conditions that the major challenges in expanding the charging infrastructure in the distribution grids can be solved technically and economically viably. The developed methods and analytical tools can also be applied to future R&D topics in the context of sustainable energy storage. The demonstration and investigation of this model application at the distribution grid level is thus contributing significantly to the success of the energy and transport transformation.

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## Quality Control of Battery Cells in the Production Process

Ensuring reliable production processes for high-quality battery cells is a complex task in which several factors must be taken into account. The quality of battery cells can vary in many parameters such as the mechanical stability, capacity, power or lifetime. This is due to fluctuations in the material quality and also in production processes such as mixing, coating, assembly and formation. This can lead to high rejection quotas.

In order to reduce the number of rejects significantly, the production lines need real-time feedback from the production process. The end-of-line quality control of battery cells is a key instrument to identify optimization potentials early and reduce production costs. Non-destructive in-line quality control of the battery cells is thus the approach we are pursuing in the "OrtOptZelle" project that is funded by the German Federal Ministry for Education and Research (BMBF). In our battery test laboratory, mechanical, optical and electrical measurement methods are used to classify batteries. Subsequently, these non-destructive methods are validated by post-mortem analyses where the battery cells are disassembled. The components are investigated under the microscope and subjected to surface and chemical analyses.

Apart from quality control during cell production, our methods and processes can also be applied to the quality assurance of incoming goods by battery system manufacturers.

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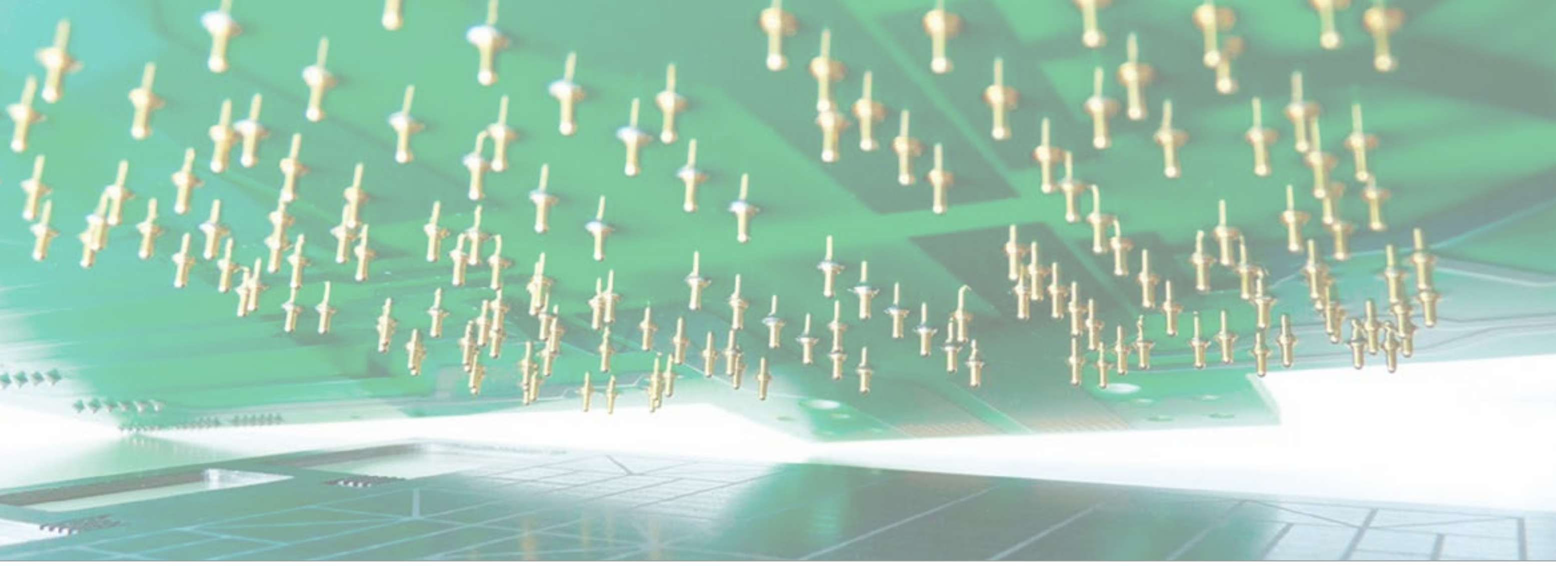
1 The new Development and Test Center for Batteries and Energy Storage Systems of Fraunhofer ISE.

2 Lithium-ion battery cells in different sizes and forms.



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## Selected Projects in 2020

- FLiBatt – Solid Lithium Batteries with Non-Woven Materials
- H2-SO – Hydrogen Technologies in the Southern Upper Rhine
- Haid-Power – Planning and Implementation of an Innovative Energy Concept for a Development and Test Center for Batteries and Energy Storage Systems in a Distribution Grid for Industry and Electromobility
- HyDrive-OWL – Detailed Concept to Expand the Regional Hydrogen Infrastructure for the Region Encompassing Lippe, Minden-Lübbecke and Bielefeld
- NAMOSYN – Sustainable Mobility with Synthetic Fuels
- OrtOptZelle – Position-Dependent Compression of Battery Pouch Cells for Lifetime Optimization
- Printsolid – Printable Solid-State Lithium-Ion Batteries
- NESSI – Novel Si Anodes for Solid-State Lithium-Ion Batteries

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

# Power Electronics, Grids and Intelligent Systems

In its work on Power Electronics, Grids and Intelligent Systems, Fraunhofer ISE addresses technologies to transform the electricity system. This requires a thorough analysis of the current electricity system. We contribute to its transparency also for the general public, with our online evaluation tool "Energy Charts". Scenarios for the transformation are defined in our REMOD study, which forms the basis for our research on new technologies for the electricity grid of the future.

Now that renewable energy sources dominate electricity generation, the present focus is on converting the transport and building sectors. As a result of increasing sector integration, the electricity grid is becoming the central hub for integrating renewable energy. The digitalization needed to do this is implemented with the aid of power electronics and smart-grid technologies.

Power electronics is a key technology to integrate renewable energy and storage units. In addition, the expansion of electromobility increases the demand for power conversion systems. By applying the most recently developed semiconductors, these have become extremely compact and efficient. In our new test facility in the Center for Power Electronics and Sustainable Grids, we are working on grid-compliant behavior of converters and so-called "grid-forming" inverters.

Communication and interconnection of energy systems is also becoming increasingly important. In our new "Digital Grid Lab", we address the interoperability and digitalization of energy systems, whereby artificial intelligence methods are playing an important role. This development process is supported today by powerful approaches like "Power Hardware in the Loop" (PHIL). We are thus in the position to offer our clients the development and characterization of converters and the control technology for the next generation of energy systems.

165
Total staff

18
Journal articles and contributions to books

48
Lectures and conference papers

1
Newly granted patents

Our newsletter offers regular updates on our research milestones.

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

Photo: Fault ride-through (FRT) test facility at Fraunhofer ISE.


## Energy Charts with New Data Functions

The Energy Charts platform has analyzed data on electricity generation from various neutral sources since 2014 and makes it publicly accessible. In the "InGraVi" project, which is funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt – DBU), Fraunhofer ISE has developed the web page further such that connections between different data categories can be presented better. The design was also completely revised and optimized for mobile usage, as many users access the site via their smartphones or tablets.

The new data include the residual load, which represents the difference between consumption and renewable power, thus indicating how much conventional power is demanded. Responding to requests from many users, we have also integrated the electricity generation and consumption of pumped storage power plants. To make the graphs more easily readable, the numerical values can now be included directly in the graphs. Another new feature is the responsive map of Germany, which displays not only infrastructure data (power plants, electricity grid, transmission grid operators) but also current meteorological data from the Deutscher Wetterdienst. Users can generate their own "heat map", which displays values e.g. for solar irradiance, precipitation or the number of days with air temperatures constantly below 0 °C with color scales. The $CO_2$ price as an instrument for decarbonizing the energy system has become visible in the "Prices" category: Current prices for $CO_2$ emission certificates can be compared to the electricity exchange price. In this way, it can be assessed whether generating electricity from coal is still economical for power plant operators with respect to the market electricity price.

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1 Monthly day-ahead electricity prices and $CO_2$ emission certificate prices.

## Making Industrial Energy Systems More Flexible

How can the potentials for more flexibility due to sector integration of electricity, heat and cooling power be optimally exploited and used economically? Within the "FlexGeber" project, which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), Fraunhofer ISE has investigated novel technologies to produce heat and cooling power in this context and identified new solutions to increase energy efficiency and integrate renewable energy into the industry, trade, commerce and service sectors.

We undertook the reconstruction or extension of existing energy systems with the goal of supplying electricity, heat and cooling power efficiently and as demanded, thus creating sustainable local energy systems. For example, we extended the local heating and cooling power supply for Fraunhofer ISE, so that the supply to individual buildings could become more flexible and the energy efficiency of the whole campus be increased. Different options for expanding the heat supply for industrial companies were evaluated. We apply models to determine the effects and potentials of flexibilization by monitoring the existing and the extended systems in detail.

The results so far lead to the conclusion, on the one hand, that the current regulations and market conditions do not yet offer sufficient incentive to companies to use existing potentials for flexibilization. On the other hand, future scenarios show that new incentives such as implementing variable electricity tariffs would allow a significantly higher potential for economic utilization of existing flexibility to be tapped.

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2 Extending a cooling grid in the context of the case study.

## Smart Meter Gateway – Secure Metering and Control in the Smart Grid

Smart Meter Gateways (SMGW) are central components to digitalize the energy system. Together with modern metering devices, they form so-called "intelligent metering systems" that allow the measured values to be transferred to the meter operator in compliance with legal requirements on calibrated measurements. Beyond this, they provide a secure communication channel that can be used in connection with energy management systems to control energy-technology installations.

In the "C/sells" and "LamA" projects that are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), we are studying the communication processes of the SMGW infrastructure for application in electromobility. Together with distribution grid operators, we are investigating the control of private charging infrastructure in two Southern German pilot regions. In the context of expanding electromobility, this application case is particularly important because simultaneously charging several electric vehicles with high charging power presents a new challenge to grid stability. However, with the help of local load management and the control signals of the relevant distribution system operator (DSO), it is possible to adapt such charging processes optimally to both the customer demands and the prevailing grid situation. Fraunhofer ISE has further developed its open energy management framework, "OpenMUC", into a generic control box software to implement the control chain from the distribution grid control desk to the charging station of the customer. In addition, Fraunhofer ISE possesses comprehensive SMGW infrastructure in its new Digital Grid Lab, that can be applied to investigate further future research questions of this type.

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## How Berlin Exploits its Solar Potential: "Masterplan Solarcity"

Berlin intends to be climate-neutral by 2050 and to generate 25 % of its electricity from solar energy. In order to multiply the current 100 MW of installed PV power to the required 4400 MW, the Berlin Senate approved the "Masterplan Solarcity" in March 2020. This consists of a catalogue of measures that were developed by a group of experts and then elaborated in detail by Fraunhofer ISE. The preparation process was moderated by the Zebralog agency. The "Masterplanstudie", which Fraunhofer ISE wrote, formed a second building block.

The planning of effective measures demands detailed knowledge of market segments and market barriers within the solar market, which depend on the type of investor, building usage and the business model. Therefore, the solar potentials were determined with the help of a 3D city model for about 530,000 buildings in Berlin and assigned to the owner groups by using property information from the Lands Department. Our results show that 58 % of the solar potential in Berlin is located on residential buildings, 32 % on commercial buildings and 9 % on public buildings. 41 % of the solar potential can be allocated to private persons, 48 % to companies and cooperatives and 8 % to the City of Berlin. In combination with the investigation of decision processes in specific target groups, these data formed the basis for deriving 27 measures in nine activity areas for the "Masterplan". Successful exploitation of urban solar potentials is possible only with a comprehensive strategy and its rigorous implementation. The "Masterplan Solarcity" for Berlin is a promising example for such an approach.

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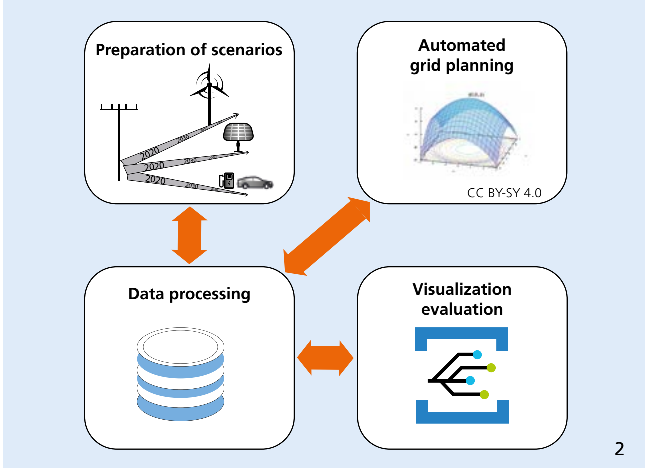
1 Intelligent measuring systems make energy efficiency analysis of energy assets in the power grid feasible.

2 Construction of a PV system on the Max Taut School by the Berlin city utility.




## Grid-Forming Converters

The increasing share of electricity generated from renewable energy sources means that increasing amounts of electricity enter the grid via power-electronic converters. Already in the near future, renewable sources of energy will be able to meet the complete energy demand for some periods of time. They thus displace generation by synchronous generators such as those used in conventional power stations. For this reason, converters must provide increasingly more functions to ensure safe and stable operation of the electricity grid.

Grid-forming converters are needed for these ancillary services. Last year, within the "VerbundnetzStabil" project that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), we developed a new concept which supports the electricity grid during extreme voltage-driven or frequency-driven faults. Furthermore, we investigate the effects of this novel control on the electricity grid as well as the grid demands and derive further specifications for the converter behavior from this investigation. On this basis, we have cooperated with other European partners to develop a draft for a corresponding test guideline. This includes proof of the basic properties of grid-forming converters, such as voltage source behavior and provision of system inertia, and also the description of procedures to estimate the interactions between the device under test and the grid or other generation systems as well as determine the reaction if grid faults occur.

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## Grid Planning and Optimizing Grid Extension

Research questions relating to stabilization of the distribution grid infrastructure and long-term planning of the target grids are gaining importance against the background of increasingly distributed electricity generation and rising electricity demand due to sector integration.

In the research project entitled "StraZNP – Strategic Target Grid Planning", Fraunhofer ISE is developing a planning tool that calculates the cost-optimized grid extension for existing and anticipated grid loads. To determine the grid load, we analyze not only load profiles that are generated with our "synPRO" tool but also social factors, technological developments, regulatory boundary conditions and current market developments. These analyses form the basis for the algorithms of the planning tool, which can calculate different planning scenarios and enables sustainable and cost-effective automation of the planning process. In cooperation with the grid operators involved, the planning process was divided into four steps and a software module was specified for each step. The opportunity to use each model independently of the other modules was of great added value for the grid operators. At the same time, the goal is to connect the modules with each other in the future so that they can then map the entire planning process.

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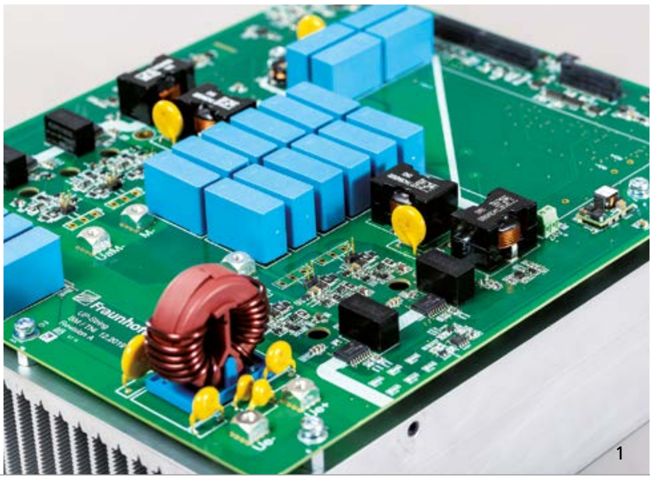
1 Characterization of a grid-forming converter in the Multi-Megawatt Lab.

2 Modules for automated planning of distribution grids.




## Photovoltaic and Battery Converters with 1500 V Systems Technology

A trend toward higher voltages has become established in photovoltaic power plant technology. System voltages of 1500 V at the module level and the connected power electronics allow reducing the associated current levels. The advantage is that less copper is needed for the current conductors and thus costs can be saved.

We have developed solutions for this as part of three projects funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). In the “MODUS” project, we took a 1500 V PV inverter with a power rating of 1 MW into operation in 2021. The modular construction with a three-level topology and 4 kHz switching frequency, combined with a fluid cooling system for the semiconductor modules, and the inductance allow an extremely compact configuration. In a lower power class, we implemented a 1500 V step-down converter with a power of 20 kW within the “UP-STRING” project. Discrete silicon carbide semiconductors with a switching frequency of 100 kHz and magnetically coupled inductance were used. Utilization of a step-down instead of a step-up converter allows the lower 1000 V voltage class to be retained with string inverters. This application is also conceivable in conjunction with 1000 V battery systems at the parking level. In the “HYBAT” project, we are currently working on a bidirectional inverter in the 150 kW power class and a switching frequency of 48 kHz in the 1500 V voltage class. In addition to stationary storage systems, we are investigating the transfer of the 1500 V voltage class also to the sector of electromobility and mobile storage batteries.

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1 Power circuit board of the bidirectional 1500 V step-down converter.

## Partial Load Optimization of Battery Chargers in PV Home Storage Systems

In the context of home storage systems becoming increasingly popular, Fraunhofer ISE has developed a hybrid inverter within the “HyBaG” joint project. It can be operated alternatively with a battery, PV system or in a hybrid mode combining both systems. The main content was to develop compact and modular battery converters, which we were able to implement by consistent application of new silicon carbide SiC components. One of the major challenges for home storage systems is that the batteries are charged within a few hours of intensive solar radiation and then are discharged over a longer period overnight at very lower power (“partial load”). For this reason, battery inverters should feature a high conversion efficiency that covers the widest possible power range.

To optimize the partial load efficiency, we investigated different approaches within the research project. Taking various evaluation parameters into account, we selected and then constructed a three-phase synchronous converter for the high-voltage battery converter. This allows the power range to be specifically adapted (to 1/3, 2/3 or full load) by activation or deactivation of individual converter bridges. For very low power loads, an additional operating mode with only one phase is activated with variable switching frequency to control with the lowest possible switching losses “boundary conduction mode” and pulsed operation “burst mode”, in which the convertor is active only for 10 % of the time. In this way, we have implemented an efficiency optimized operational management depending on electrical power.

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2 Optimized battery charger with 6 kW nominal power for high-voltage batteries.

## Contacts

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## Selected Projects in 2020

- Copernicus-Ariadne – Evidence-Based Assessment to Map out the German Energy Transformation
- HYBAT – Hybrid Lithium-Ion Battery Storage Solution with 1500 V Systems Technology, Innovative Thermal Management and Optimizing Operation Management
- LamA-connect – BSI-Compliant Charging Using Smart Meter Gateways
- UP-STRING – Bidirectional 1500 V Step-Down Converter with Cost-Optimized Circuit Topology
- StraZNP –Strategic and Targeted Grid Planning
- MAPSEN – Methods and Analyses to Determine the Impact of Decentralized Prosumers and Energy Storage on Germany's Power Generation and Electricity Grid
- TransDE – Transformation of the German Infra-structure by 2050 in Harmony with the Energy Transformation of all Consumption Sectors
- Power4re – Reliable Power Converter for the Provision of Renewable Energy

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

17800 m² laboratory area

920 m² clean room area

battery tester up to 250 kW

innovative printing technology for narrow structures less than 20 µm

test grid connected to 110 kV

2 MW grid simulator overall

40 MVA power

UVRT and OVRT tests up to 10 MW

top value of 1.1 % measurement uncertainty in CalLab PV Modules

testing accreditation for 56 standards

WORLD'S ONLY ACCREDITED PROVIDER OF COMPREHENSIVE TESTING ACCORDING TO ISO 9806:2017

Three air-handling units for flow rates ranging from 80 to 5000 $m^3/h$

Structures of 100 nm to 100 µm generated by interference lithography

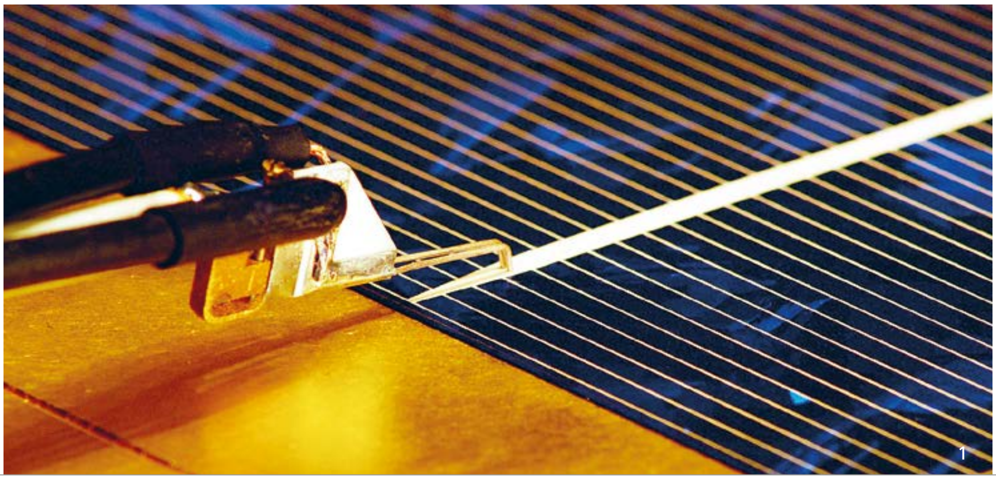
NAP-XPS equipment for material characterization at up to 50 mbar and 5 °C to 1000 °C

# R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of 17,800 m² – including 920 m² of clean-room area – and extremely modern equipment and facilities are the basis for our competence in research and development. Our goal is to find promising technological solutions and transfer these into the economy and society. Our industrial partners profit from the know-how of our staff as well as the continuous expansion of our technical infrastructure. Particularly small and medium-sized enterprises without their own R&D departments gain access to high-performance laboratory infrastructure and excellent research achievements by cooperating with Fraunhofer ISE.

In our seven laboratory centers and four production-relevant technological evaluation centers, we develop new products, processes and services and optimize existing ones. Complementing these activities, Fraunhofer ISE offers various testing and certification procedures to commercial enterprises and research institutes in its seven accredited laboratories. At present, the Institute has two calibration and five test laboratories with modern technical equipment that are accredited by the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body).

CalLab
PV Cells




## Calibration of Solar Cells

CalLab PV Cells at Fraunhofer ISE offers the calibration and measurement of solar cells representing a wide range of PV technologies. It cooperates with companies and institutes at national and international levels to develop accurate measurement methods for new types of technologies. CalLab PV Cells 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). In cooperation with PV manufacturers, and with the support of the German Federal Ministry for Economic Affairs and Energy (BMWi), 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. Our clients profit from the further development of our existing test rigs, which now offer even greater accuracy and shorter measurement times. Newly developed and improved optics to homogenize the illumination intensity play an important role in these improvements. They form the basis for the accurate measurement of large-area, multi-junction solar cells for terrestrial applications, such as perovskite-silicon tandem cells. Furthermore, various multi-source solar simulators allow us to make measurements of multi-junction solar cells under almost any standard conditions, such as those needed for space and concentrator applications.

In a new research field, we are addressing the measurement of photovoltaic cells for laser power conversion, 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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**Multi-Junction and Concentrator Cells**
Dr. Gerald Siefer
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### Standards and Specifications

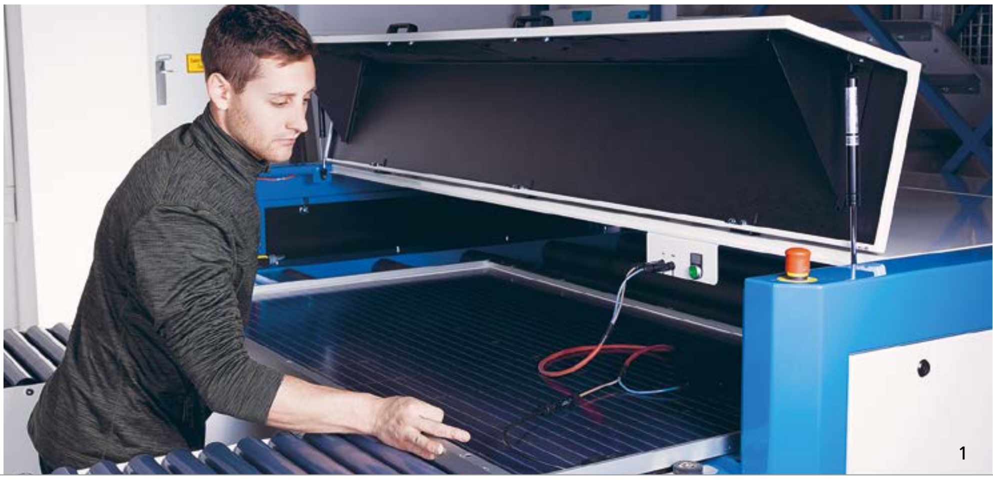
» Solar cell calibration according to IEC 60891 and the standards of the IEC 60904 series under diverse reference conditions such as:
- AM1.5g (IEC 60904-3)
- AM0 (ISO 15387)
- AM1.5d (ASTM G173-03)

» Accreditation as a calibration laboratory according to DIN EN ISO/IEC 17025

» Further measurements according to IEC 61853

1 Shadow-free 4-wire contacting of a silicon wafer solar cell.

CalLab
PV Modules



## Calibration and Performance Tests of PV Modules

In our accredited calibration laboratory, we calibrate PV modules for production lines around the world accurately, quickly and reliably. With an internationally leading measurement uncertainty of only 1.1 %, confirmed by the Deutschen Akkreditierungsstelle DAkkS (German Accreditation Body), reference objects 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. At present, increasing numbers of large-format modules with nominal power exceeding 500 W, sometimes even 600 W, are entering the market. We are working on being able to offer accredited calibration also for these formats soon.

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, which is a clear advantage for investors in PV power plants. Based on our accurate performance tests in the calibration laboratory, we 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 also generate or verify PAN files based on our accurate measurement data.

In close cooperation with researchers from the cell development laboratories, we are already preparing methods to characterize modules that are based on next-generation, high-efficiency cell technologies such as perovskite-silicon tandem solar cells.

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.

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### Standards and Specifications

- » Accreditation as a calibration laboratory according to DIN EN ISO / IEC 17025:2018
- » 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 Electroluminescence testing as quality control.

TestLab
PV Modules

## Quality Assurance of PV Modules

In our TestLab PV Modules, we investigate the quality and reliability of PV modules. The accredited laboratory is equipped with cutting-edge and innovative testing facilities for standard and advanced testing procedures.

In TestLab PV Modules, we identify potential weaknesses of modules and analyze causes of damage, also to clarify questions relating to guarantees. We advise our clients on the definition of cost-effective and time-efficient testing programs as well as on individual quality criteria. In co-operation with our partner, the VDE Prüf- und Zertifizierungsinstitut, we offer product certification according to international quality and safety standards.

The field of new cell and module concepts is evolving very dynamically at present. Modules are becoming larger and generate more power, and the diversity of cell and connection concepts is increasing. Separated cells, shingle technology with and without connectors, multi-wire and tandem technologies play a major role. The application areas are also widening; dedicated products e.g. for building or vehicle integration bring new challenges concerning the boundary conditions for module testing. Often, the specifications in existing standards are not clear concerning the testing of such modules.

We thus investigate the applicability of testing and measurement procedures for these technologies in an early phase and develop adapted methods. In doing so, we follow the goal of highest accuracy and practical relevance. We contribute our experience and results within international standardization bodies.

For special climatic conditions in deserts or tropical locations, we offer our model-based testing programs. They ensure reliable operation of PV modules and components also in harsh climates.

Fraunhofer ISE, with its accredited test laboratories, is greatly trusted around the world as independent testing bodies. We support our clients in improving the bankability of their innovative products and projects by offering customized testing procedures for modules and benchmark these products against state-of-the-art technologies.

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### Standards and Specifications

» Accreditation according to DIN EN ISO / IEC 17025 for following PV module standards
- IEC 61215-1 / -2:2016 Terrestrial photovoltaic (PV) modules – Design qualification and type approval
- IEC 61730-1 / -2:2016 PV Module safety qualification
- UL 1703 / UL 61730 / UL 61215
- IEC TS 62804-1:2015 Modules – Test methods for the detection of potential-induced degradation (PID)
- IEC TS 62782 Cyclic Mechanical Load

» Furthermore, we offer:
- Technical Due Diligence
- Qualification of materials and components
- Damage and fault analysis
- Special tests (salt mist and sand abrasion)

1 PV modules are wrapped in copper foil for the dielectric strength tests.

TestLab
Solar Façades

## Characterization of Façades and Building Components

In TestLab Solar Façades, we characterize transparent, translucent and opaque materials, test building envelope 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 that convert solar energy into electricity or heat.

TestLab Solar Façades is accredited for determining transmittance, reflectance, g value and U value by measurement and calculation. Our speciality is testing objects that 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, such determining 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 (bidirectional scattering distribution function) are determined goniometrically and are used in simulation programs to evaluate daylight use and glare, e.g. for offices with complex window and solar-shading systems. Studies on user preferences and visual comfort are carried out in rotatable daylight measurement rooms.

In addition, TestLab Solar Façades is the European Regional Data Aggregator (RDA) for the National Fenestration Rating Council (NFRC). European glazing manufacturers who intend to address the North American market with their products must submit their data sets to the RDA for review before they are entered into a data bank in cooperation with the Lawrence Berkeley National Laboratory (LBNL). Fraunhofer ISE advises and supports European manufacturers during this submission process.

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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
- Notification for optical and calorimetric testing according to EN 572-9, EN 1096-4, EN 1279-5, EN 1863-2, EN 12150-2, EN 14179-2, EN 14449
- Thermal conductivity and U value according to ISO 8302, DIN EN 673, DIN EN 674
- Solar Reflectance Index (SRI) according to ASTM E1980
- Regional Data Aggregator (RDA) for IGDB data sets from European glazing manufacturers on behalf of the National Fenestration Rating Council (NFRC)

1 Rotatable daylighting test rooms.

TestLab
Solar Thermal
Systems

## Testing of Collectors, Storage Tanks and Systems

Integrated system solutions with the highest possible share of energy from renewable sources are essential to reduce $CO_2$ emissions. In order to ensure that technologies can be evaluated according to this criterion, it is necessary to have relevant technical parameters, which Fraunhofer ISE provides to its clients. The portfolio of the accredited TestLab Solar Thermal Systems covers testing as the basis for market access and certification of all types of solar thermal collectors and thermal storage units, as well as complete systems and their components for space heating, domestic hot water and air conditioning. For solar air-heating collectors, we are the only test laboratory in the world that is accredited to conduct complete testing according to ISO 9806:2017. Interdisciplinary cooperation with the accredited TestLab PV Modules allows us also to offer measurements for complete certification of PVT collectors. To test hybrid heating systems, e.g. the combination of solar solutions with heat pumps, we work together with the accredited TestLab Heat Pumps and Chillers.

Our clients profit equally from the comprehensive knowledge of our staff and the modern laboratory facilities with state-of-the-art technology. Our indoor test stand with a solar simulator achieves high reproducibility, which is especially important in the context of product development. Our outdoor test stands are designed for testing both large-area collectors and concentrating collectors. In addition to many tests specified in standards, we also test the mechanical stability of mounting systems, PV modules and solar thermal collectors individually in the temperature range from –40 °C to +90 °C, as required by our clients. With in situ characterization, TestLab Solar Thermal Systems can also measure systems for our clients in the field, e.g. in district heating networks. We carry out factory inspections for our clients around the world, also with remote procedures, within the Solar Keymark certification program.

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**Standards and Specifications**

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

1 Test rig for the performance test of a façade-integrated, air-heating solar collector.

# TestLab
Heat Pumps
and Chillers

## Measurement and Testing of Heat Pumps

TestLab Heat Pumps and Chillers offers the most modern technology for developing, testing and characterizing heat pumps and chillers, as well as their components. The modular test rig concept makes it feasible to test different types of technologies and system configurations over a broad spectrum of operating conditions with different heat transfer media (air, water, brine). In addition to electrically driven systems with a connection power of up to 30 kW, thermally driven equipment (based on heat, natural gas or a test gas) can also be measured. The laboratory is equipped with an integrated safety concept that allows components and systems with flammable refrigerants or ammonia to be set up and tested.

Test objects with heating or cooling power of up to 100 kW (50 kW in calorimetric operation) can be measured in a calorimetric double climatic chamber at temperatures between –25 °C and +50 °C and 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 thermal power range up to 75 kW. In the three air-handling units, the air stream (80 m³/h to 5000 m³/h) can be conditioned in the temperature range from –15 °C to +50 °C and relative air humidity from 15 % to 95 %.

In our laboratory, which is accredited according to ISO / IEC 17025, we test systems according to all common standards and technical codes. Beyond standardized methods, we cooperate with our clients to develop individual measurement procedures that enable efficient and cost-effective development and optimization of devices and more complex systems by realistic, dynamic measurement sequences, including hardware in the loop. When doing so, it is possible to transfer the measured and operating data in real time via our secure connection to an external computer and to control the appliance under test. 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 is used to address specific questions, particularly in the fields of structural dynamics and acoustics.

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### Standards and Specifications

- » Accreditation according to 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 Directive
- » Tests for the Heat Pump Keymark
- » Tests for Passivhaus-Institut (PHI) certification
- » Staff certified according to the F-gas regulation, Class I.

1 Side view of sub-circuits to condition the hydraulic heat sinks or sources of our test stand.

TestLab
Power Electronics

## Characterization of Power Electronic Equipment

The accredited TestLab Power Electronics offers testing of electric units and systems in the high-power range up to approximately 10 megawatts. In doing so, it can draw on the extensive equipment of the Center for Power Electronics and Sustainable Grids and profits from its own connection to the 110 kV grid.

The equipment in the laboratory enables us to test the electric properties of inverter systems, characterize them according to current grid codes and carry out climatic-chamber tests to clients' specifications. We mainly test PV and battery inverters, but also combustion engines e.g. combined heat and power (CHP) plants or loads such as rapid charging stations for electromobility. The laboratory is equipped with different transformers, FRT test facilities (up to 10 MVA), a grid simulator (up to 1 MVA), DC sources (each 1 MW), protection testing device and a RLC load for anti-islanding tests (400 kVA).

Furthermore, we offer our clients field measurements, of large PV or wind power plants, for instance. 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 directly on-site with our 4.5 MVA LVRT test container. A flexibly configurable PV generator with a rated power of 1 MWp is available at our outdoor test field for testing inverters, among others.

We measure power-generating units according to international grid codes (e.g., for Germany, China or Great Britain) and determine the efficiency of power electronic equipment with high accuracy. We also support our clients in modelling power-generating units and plants at the grid connection point. When planning and conducting measurement campaigns, we always react flexibly to the requirements of our clients and offer detailed consulting and support, also in the preliminary phases.

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### Standards and Specifications

- Accredited according to DIN EN ISO / IEC 17025
- Determination of the electrical properties of power generation units for grid connection codes (FGW TR3: medium-voltage, high-voltage and extra-high-voltage grids, DIN VDE V 0124-100: low-voltage grid)
- Modelling and validation of the electrical properties of power generation units and plants (FGW TR4)
- Further standards concerning efficiency (DIN EN 61683, DIN EN 50530), wind turbine systems (DIN EN 61400-21) and in-house procedures (bidirectional efficiency)

1 Device under test in the Multi-Megawatt Lab including a 1 MVA grid simulator.

## Center for High Efficiency Solar Cells

In the "Center for High Efficiency Solar Cells", we develop technologies to achieve the highest photovoltaic efficiencies at an internationally leading level. High efficiency solar cells are applied not only in conventional solar modules but also to supply electricity for satellites, electric vehicles, autonomous sensors and electronic devices.

Fraunhofer ISE holds several world records for high efficiency solar cells, including for front and back contacted silicon solar cells (26.0 %) and for multicrystalline silicon (22.3 %). Moreover, the world's best monolithic III-V-silicon tandem solar cell (34.5 %) and four-junction solar cell (46.1 % under concentrated light) were developed at Fraunhofer ISE.

In order to further strengthen this leading position, we are currently moving into a new laboratory building that will be officially opened in 2021. This is equipped with clean-room facilities that allow us to meet future technological challenges. Here, we can test and optimize advanced PV technologies in modern laboratories occupying an area of more than 1000 $m^2$.

In parallel to further develop silicon and III-V technology, one focus of the new laboratory is on the combination of these two materials: High efficiency silicon-based tandem cells are among the most promising photovoltaic technologies for the future. With its new laboratory building, in the future Fraunhofer ISE will continue to develop pathbreaking new types of solar cells and contribute to the competitiveness of the German PV industry with innovative processes and technologies.

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Dr. Frank Dimroth
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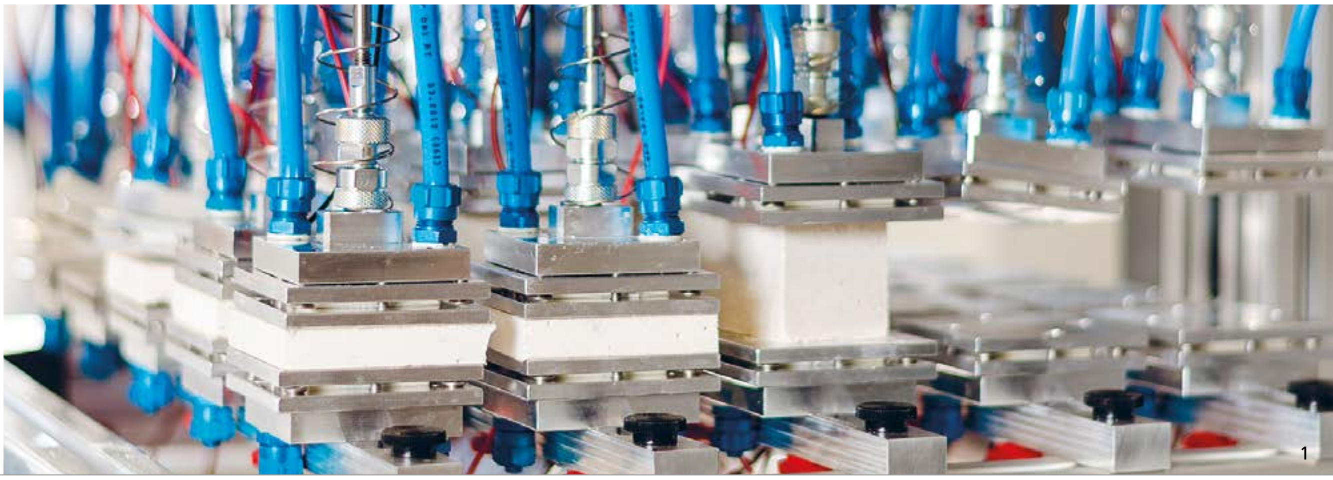
**Technical Facilities**

» Flexibly usable clean room with a floor area of 740 $m^2$
» Further laboratories with a floor area of 340 $m^2$
» High-temperature diffusion ($BBr_3$, $POCl_3$)
» High-temperature oxidation (in dry and humid atmospheres)
» Ion implantation (P, B, H, Ga, Si)
» Wet-chemical processes for purification and structuring
» Wafer-bonding technology
» Plasma technology (PECVD and etching)
» Yellow-light zone for photolithography and laser lithography to create microstructures with front to back alignment
» Atomic layer deposition (ALD)
» Processing of flexible wafer dimensions up to 157 × 157 $mm^2$
» Thermal and electron beam evaporation of metals and dielectric layers
» Electro-plating
» Extensive characterization facilities for materials and components

1 The new laboratory building of the Center for Highest-Efficiency Solar Cells in Freiburg.



1

## Center for Material Characterization and Durability Analysis

In this center, we combine broad technical competence on testing and measuring many diverse materials. We can simulate different operating and load scenarios such as extreme climatic conditions and investigate their effect on material properties.

We support industrial partners primarily in the following application fields:

» Photovoltaic cells, modules and systems
» Building technology
» Energy storage
» Polymers
» Surfaces and coatings

Furthermore, we work inter-sectorally for many other industrial branches such as the consumer goods, electrical and chemical industries. We possess special expertise on semiconductor materials, thermochemical and porous materials, phase-change materials and coatings on glass and metals. Another focus is on the analysis of heat transport properties and optical properties of materials.

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**PV Modules**
Daniel Philipp
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**PV Cells**
Dr. Martin Schubert
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### Technical Facilities

With our cutting-edge equipment, we offer our partners a wide spectrum of valuable, application-oriented analyses and investigations:

» Electrical analytics: accurate determination of electrical parameters of solar cells and modules
» Optical analytics: imaging microscopic and camera-based measurement methods to determine material properties of solar cells and modules
» Transmission and reflection measurements with FTIR spectrometry and integrating spheres
» Surface analytics: microscopic investigation of surfaces with highest resolution applying scanning electron microscopy and other methods
» Confocal Raman microscope with AFM for high-resolution characterization of surface morphology and mobile AFM to investigate large component surfaces
» Contact angle measurement to determine surface energy
» Thermal and temperature analytics
» Measurement of heat capacity and conductivity; degradation and corrosion investigations applying TGA-MS
» Determination of the permeation of moisture and other test molecules through encapsulation and barrier materials
» Structural analysis of materials
» Structural analysis of porous materials by adsorption of $N_2$ and $CO_2$
» Structural analysis applying X-ray diffractometry (XRD) and diffuse reflectance FTIR spectroscopy (DRIFTS), combined with in situ reaction chambers
» Accelerated aging: flexibly combinable artificial weathering with temperature, humidity and (UV) radiation as well as mechanical loads
» Outdoor weathering: exposure and monitoring in different climatic zones

1 Equipment for accelerated thermal cycling of materials, particularly composite materials and building materials.

## Center for Optics and Surface Science

In the "Center for Optics and Surface Science", we develop optically functional surfaces for numerous applications.

Within coating technology, we work on solutions based on sputtering for thermal use of solar energy, photovoltaics, energy-efficient buildings and hydrogen technology. The applications include reflectors and absorbers for solar thermal power plants, charge-carrier-selective electrodes for photovoltaics, and solar-control coatings as well as optically switchable systems for energy-efficient buildings. In addition to optimizing the optical properties, we tailor thin-film stacks to meet the relevant specifications for the final product (e.g., long-term stability outdoors or scalability to industrial production scales). Our spectrum of services encompasses feasibility studies, small-series production and product developments up to complete industrial prototypes.

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

We develop and characterize optical components for concentrator photovoltaics and solar thermal power stations. Parallel to coating development, the evaluation of reflectors and absorbers is a further focus of our work. For example, we quantify beam dilation by surface scattering and soiling and the shape accuracy and stability of reflectors as a significant contribution to optimization and quality assurance.

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### Technical Facilities

- » Modern sputtering equipment with a coating area of up to 1,5 × 4 $m^2$ with a maximum height difference (pitch) of 16 cm
- » Substrates: flat and curved glass panes, polymer films, and metal sheets and pipes
- » Interference lithographic equipment to produce master structures with structure details between 100 nm and 100 µm homogeneously over areas of up to 1.2 × 1.2 $m^2$
- » Nano-imprinting and hot-embossing equipment to transfer microstructures and nanostructures onto prototypes
- » Deflectometry, Photogrammetry and 3D laser scanning to determine shape accuracy and stability of objects and concentrator optics
- » Plasma-etching equipment to transfer imprinted structures onto non-polymer materials
- » Characterization of optical and microstructural properties: Fourier spectrometry, scanning electron microscopy (SEM), atomic force microscopy (AFM), goniometry to quantify scattering and beam dilation (3D scanning photogoniometer, VLABS: very low angle beam spread)

1 Horizontal sputter coater with a substrate area of 1,5 × 4 $m^2$.


## Center for Heating and Cooling Technologies

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.

A further thematic focus of our work is the development and evaluation of components for natural refrigerants such as propane. Our entire laboratory is thus equipped for work with flammable refrigerants and allows us to develop and optimize components for propane cooling circuits. We are working specifically on methods to reduce the amount of refrigerant needed. Furthermore, we cooperate with our partners to develop individual measurement procedures, which make the development and optimization processes of devices and more complex systems time-efficient and cost-effective with realistic, dynamic test sequences, including hardware in the loop. We also support our partners in evaluating the acoustic intensity and the long-term stability of components and cooling circuits.

To model and dimension heat exchangers, cooling circuits and systems, we also apply simulation tools.

**Dr. Peter Schossig**
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### Technical Facilities

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

1 Efficient cooling circuit developed at Fraunhofer ISE using propane as the climate-friendly refrigerant.

## Center for Electrical Energy Storage

In the "Center for Electrical Energy Storage", Fraunhofer ISE offers R&D services concerning battery materials and cells. We develop and characterize novel battery materials, process and quality control technologies and new cell architectures. Our battery engineering encompasses the development of optimized battery modules and systems including interconnection technology, safety features, thermal management, battery management with accurate algorithms to determine the state of charge and state of health as well as optimized charging and operating control strategies. We treat very diverse applications in the field of system integration and storage operation management, including stationary, commercially and industrially used battery storage units as well as electromobility.

Our extensive laboratory facilities allow the electrical, thermal and mechanical characterization of battery cells, modules and systems according to widely used standards. In addition, we conduct tests on cycling and calendric aging. To address R&D questions, we apply modern simulation tools and develop behavior models and spatially resolved models. These are validated by measurement campaigns in the laboratory.

Furthermore, we offer techno-economic evaluation at all stages of the value chain. To do so, we apply a comprehensive cost calculation tool. For system investigations, we integrate our own battery models into system models – for simulation-based dimensioning and optimization of PV-battery systems, for example – and thus make it feasible to calculate the levellized cost of electricity and electricity supply costs over a predefined period of time.

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Dr. Daniel Biro
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**Technical Facilities**

» Processing chain for the production, processing and characterization of battery cells and new materials
» Inert processing chain to investigate solid-state electrolyte batteries and component materials
» Test circuits for cycling battery cells and measurement systems for electrochemical characterization of new battery chemistry
» Battery test circuits up to system level with 250 kW (1000 V, 600 A)
» Climatic chambers with safety equipment
» Test rigs for complete PV home storage systems up to 15 kW (hardware in the loop)
» High-accuracy coulombmetric test stand
» Isothermal battery calorimeter
» Test facilities for DC applications, e.g., for lamps
» Electronics laboratory for the development of battery management systems and electronics for small PV systems
» Off-Grid Laboratory: Testing and measurements for the characterization and certification of small PV-battery systems (pico-PV systems and Solar Home System kits), components (e.g., charge controllers) and DC-powered products
» PV-battery-diesel system test stand

1 Working with the Glove Box.


## Center for Fuel Cells, Electrolysis and Synthetic Fuels

In the "Center for Fuel Cells, Electrolysis and Synthetic Fuels", catalytic materials, components and sub-systems are tested and characterized with scientifically based methods for applications in the fields of PEM electrolysis, PEM fuel cells (particularly for mobile applications), Power-to-Gas (PtG), Power-to-Liquid / Chemicals and highly efficient, clean combustion engines. We have excellent technical infrastructure and equipment. Our many years of expertise in constructing and operating experimental setups and test rigs, from the single cell to fully automated miniplant systems, enable us both to investigate fundamental scientific questions in research projects and to develop customized technological solutions on commission to clients.

**Prof. Christopher Hebling**
**Phone +49 761 4588-5195**

### Technical Facilities

- » Test stands to characterize PEM electrolysis cells and short stacks up to 50 bar and 80 °C
- » Test stands to characterize electrolyser full stacks with a DC connection power of 200 kW and 1 MW and a current of 4,000 A
- » Test and demonstration systems to feed in hydrogen and a 700 bar hydrogen refueling station with on-site electrolysis
- » Multi-channel impedance spectroscopy for spatially resolved characterization of full-format single fuel cells
- » Multi-channel impedance spectroscopy for simultaneous single-cell monitoring of fuel cell short stacks
- » Automated test stand to characterize fuel cell short stacks up to 20 kW / 1,000 A
- » Nine automated single-cell test stands for in situ characterization of fuel cell components
- » Extensive process technology and analytics for research on producing membrane-electrode assemblies
- » 24 / 7 miniature plants to synthesize liquid fuels from $CO_2$-rich input gases for highly dynamic operation, including analytics with high-resolution measurement technology
- » Walk-in climatic chamber
- » Eightfold high-pressure reactor system (up to 100 bar) to screen catalysts
- » Screening of catalysts, e.g., to investigate light-off behavior and determine secondary emissions from gas mixtures, including by FTIR
- » Kinetic investigation of catalyst powders (up to 80 bar), including FTIR / GC-WLD analytics
- » Investigation of exhaust gas post-processing concepts for conventional and PtX fuels
- » High-temperature, nearly atmospheric-pressure X-ray photoelectron spectroscopy (HT-NAP-XPS)
- » Micro-computer tomography (micro-CT)
- » Standard measurement equipment such as GC-MS, GC-FID, REM / EDX, ICP-MS, FTIR-ATR
- » Test stand with a multi-channel impedance system to characterize fuel cells, stacks and systems in the climatic chamber.

1 Test stand with a multi-channel impedance system to characterize fuel cells, stacks and systems in the climatic chamber.

## Center for Power Electronics and Sustainable Grids

In the “Center for Power Electronics and Sustainable Grids”, we have our own high-voltage grid connection. Here, we develop innovative inverter systems in the power range up to several megawatts for application in current and future power grids that will be dominated by power converters.

In the Multi-Megawatt Lab, we operate various high-quality test facilities, such as a high dynamic 1 MVA grid simulator, a fault ride-through test facility for short under- or overvoltage events (up to 10 MVA) and a large climatic chamber. In addition to characterizing dynamic, grid-connected behavior, we carry out reliability and lifetime investigations for power electronic components.

In our medium-voltage laboratory, inverter systems in the power range up to 20 MVA can be operated and measured in the 20 kV grid. We develop medium-voltage inverters with the help of appropriately equipped development workplaces and test facilities to characterize novel power semiconductor components.

The investigation, development and testing of innovative power electronic systems in the low voltage to medium power range up to several hundred kW is another focus of our activities. New semiconductor technologies based on silicon carbide (SiC) or gallium nitride (GaN) enable the implementation of promising hardware designs, which we develop to preproduction maturity.

With our new power-hardware-in-the-loop (PHIL) simulator, we can model distribution grids in the power range up to 800 kVA for low voltage in our Digital Grid Lab. The grid state and the digital communications system are simulated in the HIL system. The development environment allows designing the most modern control components, e.g. based on artificial intelligence. The control room allows grid operation to be monitored and visualized and offers the connection with a digital twin of the grid (PHIL).

**Dr. Sönke Rogalla | Phone +49 761 4588-5454**
**Digital Grid Lab**
**Dr. Bernhard Wille-Haussmann | Phone +49 761 4588-5443**

**Technical Facilities**

**Multi-Megawatt Lab**

- Grid simulator (1 MVA) and DC sources (1.4 MW)
- UVRT and OVRT test facilities (up to 10 MVA)
- Climatic chamber (–30 °C to +80 °C, 10 % to 90 % r. h.)
- Anti-islanding test facility (400 kVA)

**Medium Voltage Lab**

- Medium-voltage DC source (up to 40 kV / 3 × 200 kW)
- Medium-voltage resistance (12 kVΔ / 20 kVY / 1 MW)
- Flexible MS transformer (3 to 30 kV / 2.5 MVA)

**Power Converters Lab**

- Machine emulator (160 kVA) and grid simulator (30 kW), HIL system from OPAL-RT
- High-resolution thermography camera (Videos)
- Precision magnetics and grid impedance analyzer

**Digital Grid Lab**

- Test stand for Smart-Grid control systems and communications technology
- Extensive tool suite for IP-based communication protocols

1 Control room at the Digital Grid Lab.

## SiM-TEC – Silicon Material Technology Evaluation Center

At SiM-TEC, we develop new technologies to produce silicon wafers for photovoltaics. Silicon blocks are crystallized by the process of directional solidification of multicrystalline ingots. We develop high-quality wafers by applying processes with and without seed crystals, improving material homogeneity and increasing throughput by continuous feeding of silicon during the crystallization process.

To minimize the introduction of impurities, we are studying crucible systems and coatings with greater purity. In the kerfless wafering sector, we investigate processes for mechanical treatment of surfaces and for electro-chemical porosification of highly doped silicon wafers as substrates for a subsequent epitaxial step. We are equipped with an in-line etching facility that can carry out several single-surface etching processes in electrically separate baths for the electro-chemical processing of silicon wafers.

Another focus of our work is further development of cast monocrystalline technology to produce completely monocrystalline silicon wafers from ingot crystallization. We investigate the potential of different seed configurations to increase the material quality. In particular, the introduction of specific functional defects by a combination of differently orientated monocrystalline plates "SMART seeding technology" plays a major role. It allows the wafer dimensions to be upscaled to the M6 and M12 format that have become newly established in the PV market, without changing the actual crystallization process. Various analytical options and simulation are available to analyze the residual stresses in the materials resulting from the manufacturing process.

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### Technical Facilities

- » Multi-functional etching equipment for wafer and blocks (Ramgraber)
- » Crystallization unit (PVA Tepla VGF 623 Multicrystallizer)
- » Diamond saws for silicon processing
- » Laser-marking system for silicon bricks (Vision TL 1150-BMCS)
- » Brick inspection equipment (Intego Orion Super High Resolution)
- » Grinding and polishing system (Arnold)
- » Block characterization facility (Semilab WT-2000D)
- » Inline porosification system (IporSi)
- » Optical film thickness scanner (CyberTechnologies CT-250T)
- » Light microscope (Zeiss Axiotron)
- » Universal test equipment for fracture/tensile tests (Hegewald & Peschke)

1 "Multicrystallizer VGF632" crystallization unit for directional solidification of silicon ingots.

1

## PV-TEC – Photovoltaic Technology Evaluation Center

At PV-TEC, with a floor area exceeding 2000 m², extremely modern infrastructure with flexible processing and characterization equipment is available for the development of high-efficiency silicon solar cells and related components and substrates. Subdivision into two large laboratories allows optimal adaptation to the specific demands of front-end and back-end technology. Our services encompass:

- » Evaluation and development of production processes and processing technology components
- » Development and production of advanced industrial solar cell structures
- » Characterization and development of materials, solar cells and related components
- » Development of measurement methods and methods of data analysis based on artificial intelligence
- » Process transfer with further education and training
- » Economic cost studies

We focus on core topics of production technology and measurement technique and address companies from all stages of the value chain. We have established three baseline processes, which enable industrially relevant production of PERC (Passivated Emitter and Rear Cell), TOPCon (Tunnel Oxide Passivated Contact) und SHJ (Silicon Hetero-Junction) solar cells. We extend this e.g. with diffusion and laser processes to create selective emitters, deposition processes to produce doped poly-crystalline silicon layers or printing processes for extremely fine linear contacts with contact widths of less than 20 µm. This ensures that high-quality, continually optimized baseline processes for the most important routes of silicon solar cell technology are available in PV-TEC. Furthermore, we are preparing for the pilot production of tandem solar cells. Another focus of our work is the highly accurate characterization from the initial substrate to the complete component.

Dr. Ralf Preu
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### Technical Facilities

**PV-TEC front-end**

- » Wet-chemical batch and in-line equipment for texturing, purification and single-surface processing
- » Fully automated tubular furnace facility for diffusion, oxidation and deposition of polycrystalline Si layers
- » Fully and partly automated PECVD equipment to deposit dielectric films, as well as intrinsic and doped amorphous Si films
- » PVD (physical vapor deposition) equipment to deposit layers of metals and transparent conductive oxides (TCO)
- » In-line, automated wafer inspection system for spatially resolved optical and electrical characterization

**PV-TEC back-end**

- » Fully and partly automated laser and printing equipment for structuring and metallization with stationary and dynamic sample processing
- » Innovative in-line furnaces for contact formation and regeneration
- » Flexible in-line solar cell characterization equipment for different formats and contact structures
- » Highly flexible development laboratories for printing and laser processes, as well as detailed component analysis

1 PV-TEC front-end: In-line PECVD multi-chamber vacuum deposition equipment.

## Module-TEC – Module Technology Evaluation Center

The industrial production equipment and multifaceted analytical platforms in Module-TEC offer extensive opportunities to develop interconnection and encapsulation technologies for PV modules. The processing of innovative materials can be tested, and prototype modules as well as pilot-run series for test and demonstration purposes can be produced. Depending on the research question and the stage of development, modules are produced from single-cell to full format.

In addition to the usual ribbon or wire interconnections, we work on:

» Shingle interconnections in string and matrix configurations

» SmartWire Connection Technology (SWCT™) for the interconnection of heterojunction solar cells

» Interconnection of Si-Perowskite tandem solar cells with electrically conductive adhesives

» Interconnection of back-contact solar cells with wave-shaped wires or conductive backsheets

The innovative concept of cell interconnection with electrically conductive adhesives (ECA) is one of our main research topics. ECA offers a lead-free and gentle solution for temperature-sensitive, high-efficiency cells or very thin wafers.

Modules in glass-backsheet or glass-glass technology are manufactured in our laminators. We can produce edge-sealed glass-glass modules to avoid moisture ingress or even work without encapsulant (TPedge). Additionally, we work on the development of curved modules to integrate solar cells into car roofs as well as on modules for building integration.

Our customers use the services of our Module-TEC for:

» Integration of new materials such as high-efficiency cells into modules

» Holistic development of innovative bills of material regarding costs, processability and long-term stability

» Detailed analysis and optimization of the module efficiency

**Dr. Holger Neuhaus**
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**Technical Facilities**

» Equipment for adhesive or soldered connection of full-format, half and shingle cells

» Equipment for wire-based connection (Multiwire, SWCT)

» Laminators for 60-cell and 72-cell modules (glass-glass / glass-backsheet)

» Special laminators for curved laminates or special material systems

» 3D X-ray computer tomography

» Equipment to produce polished metallographic specimens and polished cross-sections from modules

» Digital microscopy and scanning electron microscopy

» Electroluminescence and gel content analysis

1 Cell string connected with SmartWire Connection Technology (SWCT™).

1

## Con-TEC – Concentrator Technology Evaluation Center

In Con-TEC, we use our production-relevant fabrication processes to produce concentrator modules with the highest efficiency and demonstrate ways to reduce costs. Based on novel prototypes in the form of individual components or small series, we evaluate components, designs and processes. Production equipment is available for pick and place and electrical contacting of solar cells and assembled component modules.

In concentrator photovoltaics, particularly the thermal connection of the solar cell to the substrate is decisive, as the concentrated irradiation means that very large energy fluxes have to be transferred. Both our processes and the selected materials are designed for high thermal conductivity and resistance to high temperatures and temperature cycling. Furthermore, our assembly processes feature very high precision in positioning for the very small components. For the electrical front-surface contacting, we apply ultrasonic or resistance welding processes. With thin wires or metal ribbons, we achieve small bonding areas.

Our options and experience in selecting and processing optical silicone are unique; we use this material 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 assembled component modules. Accelerated aging tests are carried out to investigate the long-term stability of the modules or components.

We support our clients in developing and evaluating designs for components and modules for concentrator photovoltaics and in developing prototypes of optoelectronic components. In doing so, we always take the economic viability for an industrial application into account.

Maike Wiesenfarth
Phone +49 761 4588-5470

### Technical Facilities

- » Soldering and adhesive processes to assemble semiconductor components and solar cell units
  - Highly accurate positioning on small and large areas up to 600 × 1170 $mm^2$
  - Soldering under air or nitrogen atmosphere, controlled curing of conductive adhesives
  - Vacuum soldering
  - Soldering without flux, applying formic acid or activation with forming gas
- » Processes for electrical contacting on small areas
  - Bonding of thick and thin wires
  - Soldering of micro-ribbons
- » Automated and manual processes for module assembly
- » Characterization of processes with respect to adhesion, positioning accuracy and electrical functionality
- » Investigation of long-term stability
  - Climatic chambers for temperature control, also with additional stress due to elevated air humidity or applied reverse voltage
  - Irradiation of optical components or encapsulation materials with concentrated UV radiation

1 Accurate alignment of the lens plate with respect to the solar cell is necessary for good performance of the CPV module.

# Events in 2021 with Participation of Fraunhofer ISE

All information is based on data available up to the editorial deadline. Please understand that changes may occur at short notice due to the coronavirus pandemic. We will keep you up to date at www.ise.fraunhofer.de/en/events-and-trade-fairs

**Bau 2021 ONLINE**
digital
13.01. – 15.01.2021

**FC Expo**
Tokio, Japan / hybrid
03.03. – 05.03.2021

**SPIE Photonics West – Digital Forum**
digital
06.03. – 11.03.2021

**ISH digital 2021**
digital
22.03. – 26.03.2021

**CPV-17**
digital
12.04. – 14.04.2021

**Hannover Messe**
digital
12.04. – 16.04.2021

**Silicon PV**
digital
19.04. – 22.04.2021

**Berliner Energietage**
digital
21.04. – 28.04.2021

**E-world energy & water**
Essen, Germany
04.05. – 06.05.2021

**36. PV-Symposium**
Freiburg, Germany
18.05. – 20.05.2021

**HOPV 21 online**
digital
25.05. – 28.05.2021

**EMRS Spring Meeting**
digital
31.05. – 03.06.2021

**SNEC PV Power Expo**
Shanghai, China
02.06. – 05.06.2021

**WHTC und f-cell HFC**
digital
20.06. – 24.06.2021

**48th IEEE Photovoltaic Specialists Conference**
Miami-Fort Lauderdale, USA / hybrid
20.06. – 25.06.2021

**Smarter E / Intersolar Europe**
Munich, Germany
21.07. – 23.07.2021

**ISHPC**
Berlin, Germany
22.08. – 25.08.2021

**38th EU PVSEC**
Lisbon, Portugal
06.09. – 10.09.2021

**IAA PKW**
Munich, Germany
07.09. – 12.09.2021

**f-cell**
Stuttgart, Germany
14.09. – 15.09.2021

**Solar Power International (SPI)**
New Orleans, USA
20.09. – 23.09.2021

**Battery Experts Forum**
Frankfurt, Germany
05.10. – 07.10.2021

**ECSCRM**
Tours, France
24.10. – 28.10.2021

**European Heat Pump Summit**
Nuremberg, Germany
26.10. – 27.10.2021

**Productronica**
Munich, Germany
16.11. – 19.11.2021

**MRS Fall Meeting & Exhibit**
Boston, USA
28.11. – 03.12.2021

**Battery Show Europe**
Stuttgart, Germany
30.11. – 02.12.21

**PVSEC-31**
Sydney, Australia
13.12. – 15.12.2021

# Editorial Notes

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Translation from German
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**Layout**
www.snow-design.de

**Printing**
Print Consult GmbH, Munich

FSC www.fsc.org MIX Papier aus verantwortungsvollen Quellen FSC® C084279

# Photo Acknowledgements

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Andreas Lorenz: Page 42 Fig. 1
Dirk Mahler: Pages 26, 30, 44, 49, 50, 59, 68,
71 Fig. 1, 72 Fig. 1, 73, 78, 79, 82, 83, 89, 91, 92, 93
Marek Miara: Page 86
Bernd Müller: Page 40
Tayyab Naeem: Page 45
Michael Schachtner: Page 34
Bernd Schumacher: Pages 10 (S. Vormfelde), 23
Timo Sigurdsson: Page 19
Bernd Steinhauser: Page 31 Fig. 1
Rajveer Singh: Page 63 Fig. 1
Beate Suppinger: Page 47
Andreas Wessels: Page Fig. 2
Kai-Uwe Wudtke: Pages 3, 10 (H.-M. Henning, A. Bett, K. Schneider,
S. Glunz, H. Wirth, R. Preu, C. Wittwer, P. Schossig)

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