Fraunhofer ISE

Results and Figures

Annual Report 2021/22

View into clean room access corridor in the "Center for High Efficiency Solar Cells" at the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany. The building, which was officially opened in April 2021, was financed by the German Federal Ministry of Education and Research (BMBF) and the State of Baden-Württemberg. It provides more than 1 000 m^2 of ultra-modern laboratories – 740 m^2 at clean-room standard – and an excellent infrastructure, which makes it feasible to raise the performance of solar cells based on silicon and III-V semiconductors to a new level. A central goal is to overcome the theoretical efficiency limits of conventional solar cells by applying tandem technology and thus to achieve an even higher energy yield per unit area.

Results and Figures

Annual Report 2021/22

Foreword

In 2021, Fraunhofer ISE celebrated its fortieth anniversary. We are proud that we were not only a trailblazer in the early years of solar research in Germany but also that we can continue to stimulate and accompany the German energy transition up to the present. Whereas the Institute initially had to work largely alone as a pioneer, today we are closely connected with all central institutions and actors from politics, the economy and society at large.

Forty years, which have been worthwhile and have produced results that can make us optimistic. And yet many questions still remain open: Will we succeed in living climate-neutrally by 2045 and limiting the global temperature increase to less than 2 °C or even 1.5 °C? What are the opportunities and risks of a rapidly changing energy system that will do without fossil fuels? Will it be possible to engage society successfully in the extensive new technological developments and their implementation? At our anniversary event in November 2021, we explored these questions in a panel discussion with representatives from research, politics and industry (pages 18/19).

We are currently experiencing transformation processes, not only in the energy system sector, but also when it comes to economic questions, digitalization, distribution of resources or accommodation. The corona pandemic has made us yet more aware of the urgent problems and challenges of our times in all their facets. This also applies for changes in the world of work. We are glad that we coped with this well under the difficult conditions of the past months – our gratitude is directed particularly to all staff at the Institute for their great dedication to their work.

As a result, we have succeeded in extending our research infrastructure further. In April 2021, we officially opened the new laboratory building of the "Center for High Efficiency Solar Cells". Its construction was possible thanks to funding from the German Federal Ministry of Education and Research (BMBF) and the State of Baden-Württemberg (pages 50/51). The goal here is to further strengthen the development of tandem photovoltaic technologies. In tandem solar cells, materials with different electronic properties such as III-V semiconductors, perovskites or silicon are combined. This allows the physical efficiency limit for conventional solar cells of only one single material to be overcome and offers great potential to save solar cell and module materials – an important step toward more sustainability in photovoltaics.

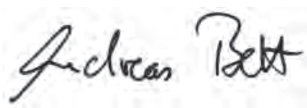
We are involved in regular exchange with research, industry and politics, also by our membership of boards and advisory committees. Due to its broad expertise, the Institute is represented at both the national and the international levels. For example, Dr. Peter Schossig, Head of Division for Thermal Systems and Building Technology, was called in 2021 as an expert to the Collaboration Programme on Heat Pumping Technologies of the International Energy Agency (HPT IEA). As heat pumps will be the dominating future heating technology in a net-zero energy system by 2045, Fraunhofer ISE is working intensively on new, commercially ready heat pump technology both for the existing building stock and also for new buildings.

In the field of hydrogen technology, which will be a fundamental pillar of the energy transition – particularly for heavy transport, shipping and industry – Prof. Christopher Hebling, Head of Division for Hydrogen Technologies and Electrical Energy Storage, was appointed as the Vice-President of the Deutscher Wasserstoff- und Brennstoffzellen-Verband (DWV – German Hydrogen and Fuel Cell Association).

High-quality, reliable and targeted communication to the outside world is essential to help our work to make a breakthrough. During the reporting period, Fraunhofer ISE was the most frequently cited Institute within the Fraunhofer-Gesellschaft. In this context, we wish to thank Karin Schneider, who headed the Communications Department for many years, for her commitment and excellent work to increase public awareness and raise the profile of Fraunhofer ISE. She left the Institute in August 2021. Her successor as the Head of the Communications Department is Christina Lotz. We wish her great success in her work.

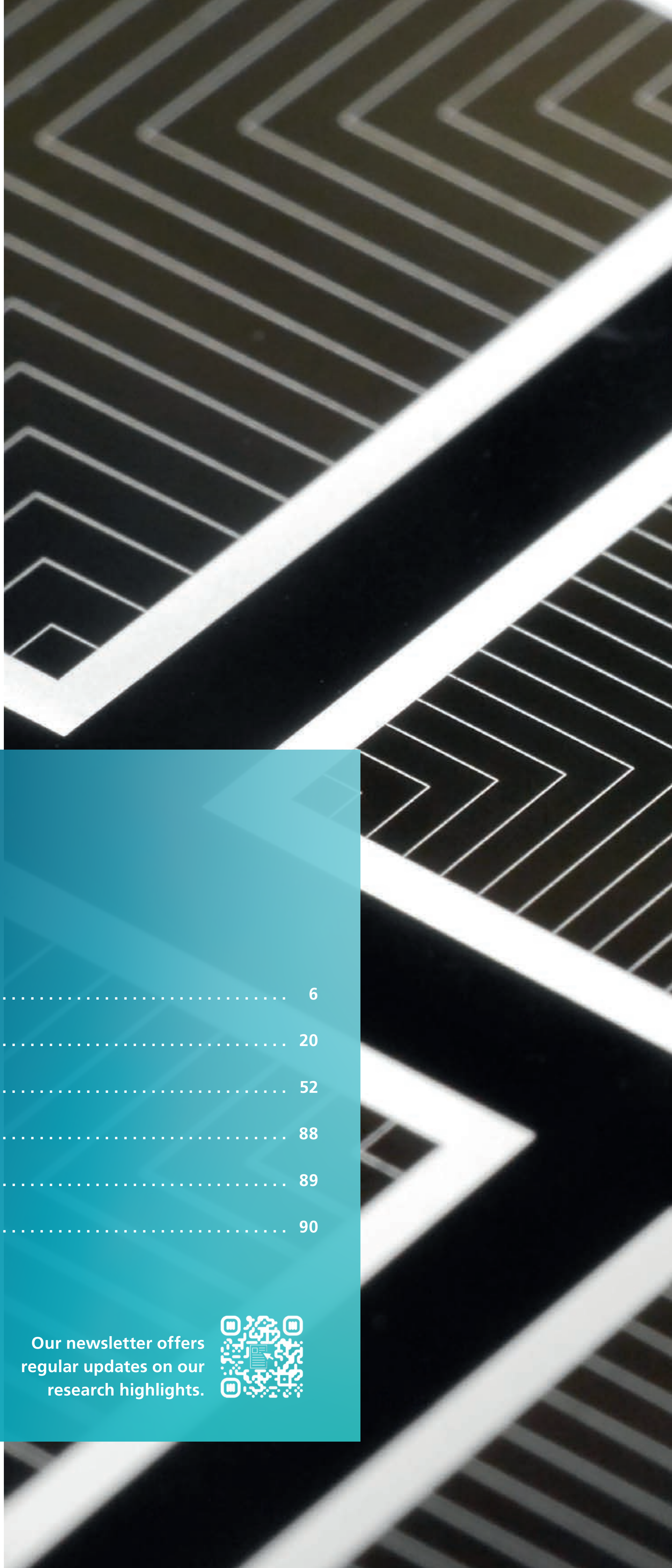
A clear but also continually adapted strategic orientation is needed to lead new technologies to success and to transfer research results to the industry and society in general (pages 22/23). We have thus defined three timeframes which allow us to concretize our mission and our guiding principles at the operative level and adapt our portfolio of research and services. We place value on a holistic approach that takes account of the aspects of sustainability, clients' requirements, science, quality, processes, interconnection and cooperation in equal measure. In future, we intend to emphasize questions of sustainability and closed material cycles more strongly, both in our research and development work but also as part of our Institute's operation.

We extend our sincere gratitude to our Board of Trustees, auditors, scholarship donors, contact persons und funding sources in the Ministries at the Federal and State levels for their support and funding of Fraunhofer ISE. We are looking forward to further cooperation, so that we can jointly advance the urgently needed task of transforming our energy system to become sustainable and socially just.



Prof. Hans-Martin Henning

Prof. Andreas Bett



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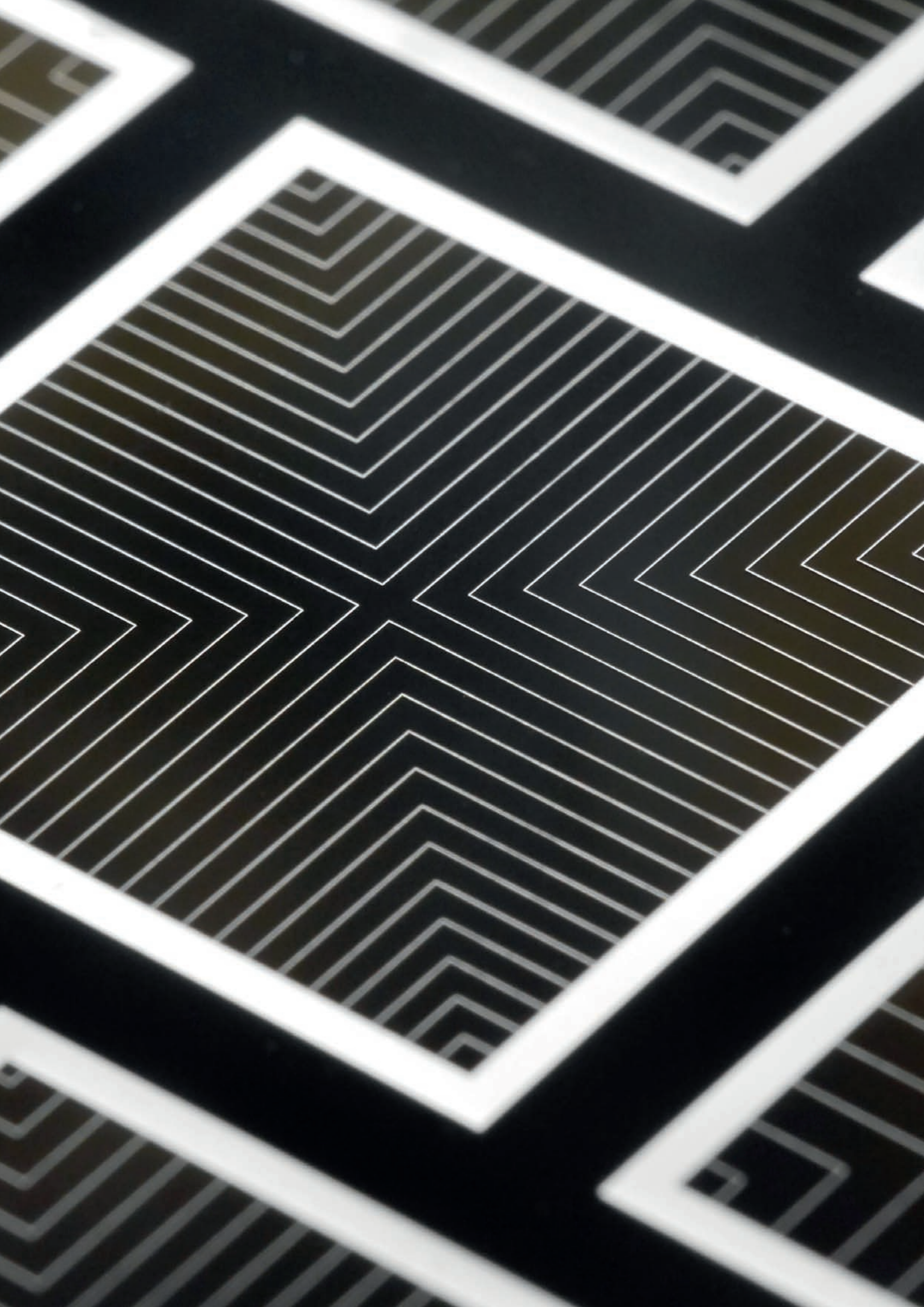
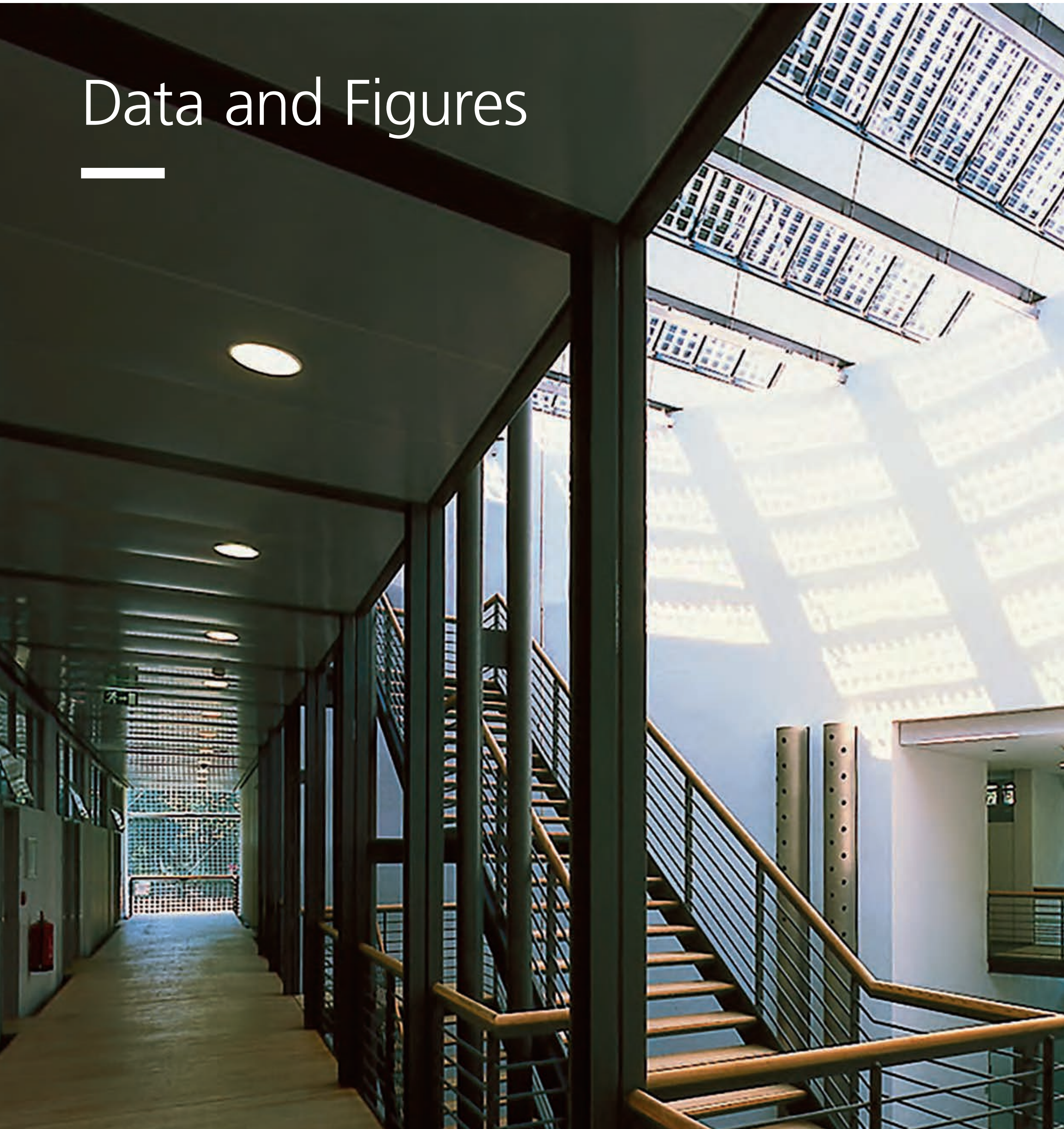
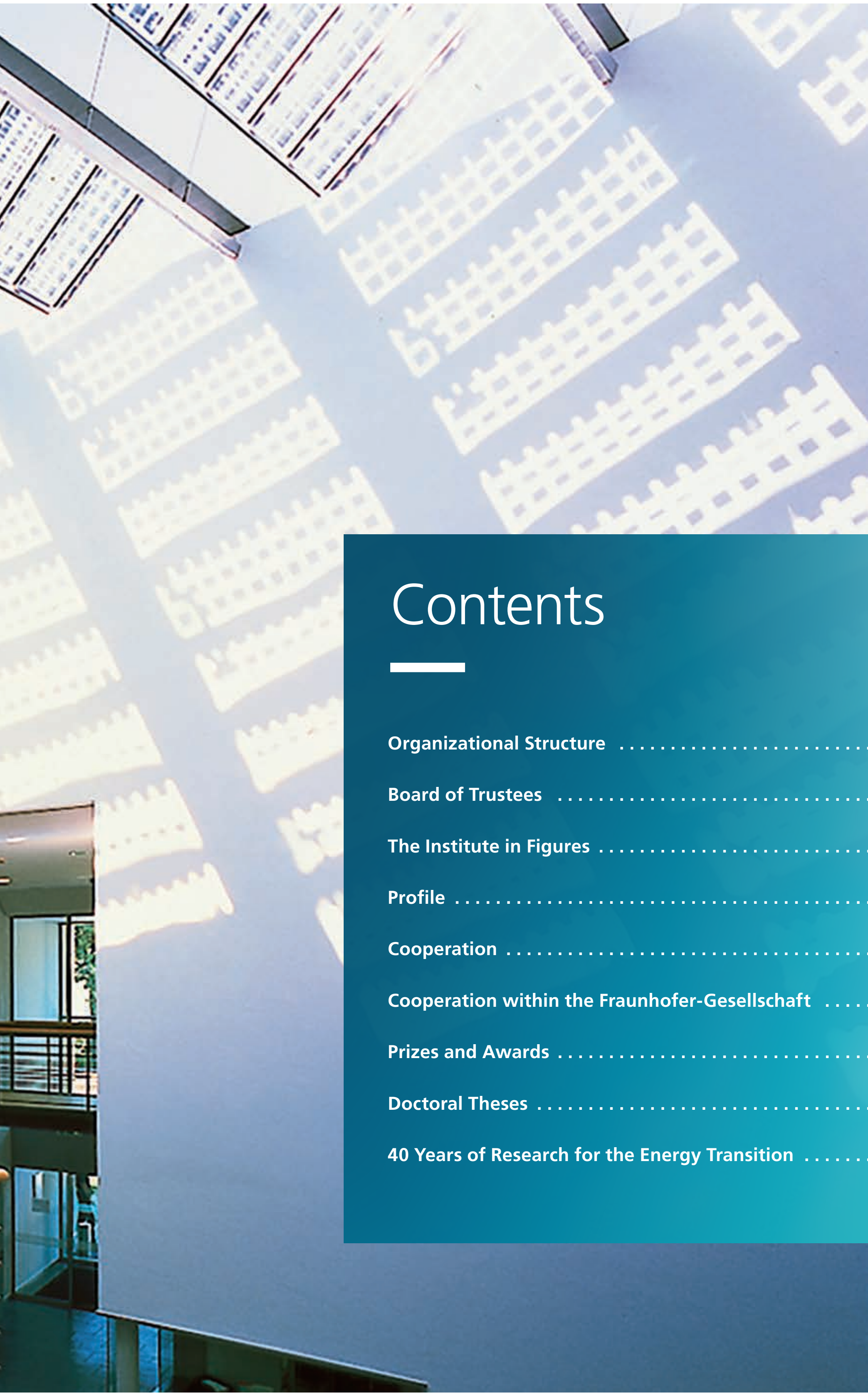
Our newsletter offers regular updates on our research highlights.



Data and Figures





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Organizational Structure









Prof. Hans-Martin Henning; Prof. Andreas Bett; Prof. Stefan Glunz; Dr. Ralf Preu; Dr. Harry Wirth; Prof. Christopher Hebling; Prof. Christof Wittwer; Dr. Peter Schossig; Saskia Vormfelde

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 experienced 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

Administrative Director

Saskia Vormfelde
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Heads of Energy Technologies and Systems Division

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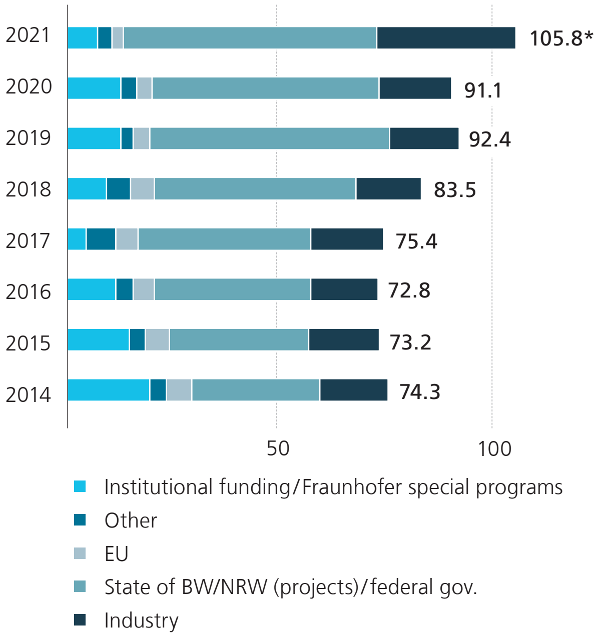
Prof. Christof Wittwer
Phone: +49 761 4588-5115

Board of Trustees

The Board of Trustees assesses the research projects and advises the Institute Directorate and the Executive of the Fraunhofer-Gesellschaft with regard to the work programme of Fraunhofer ISE.

The Institute in Figures

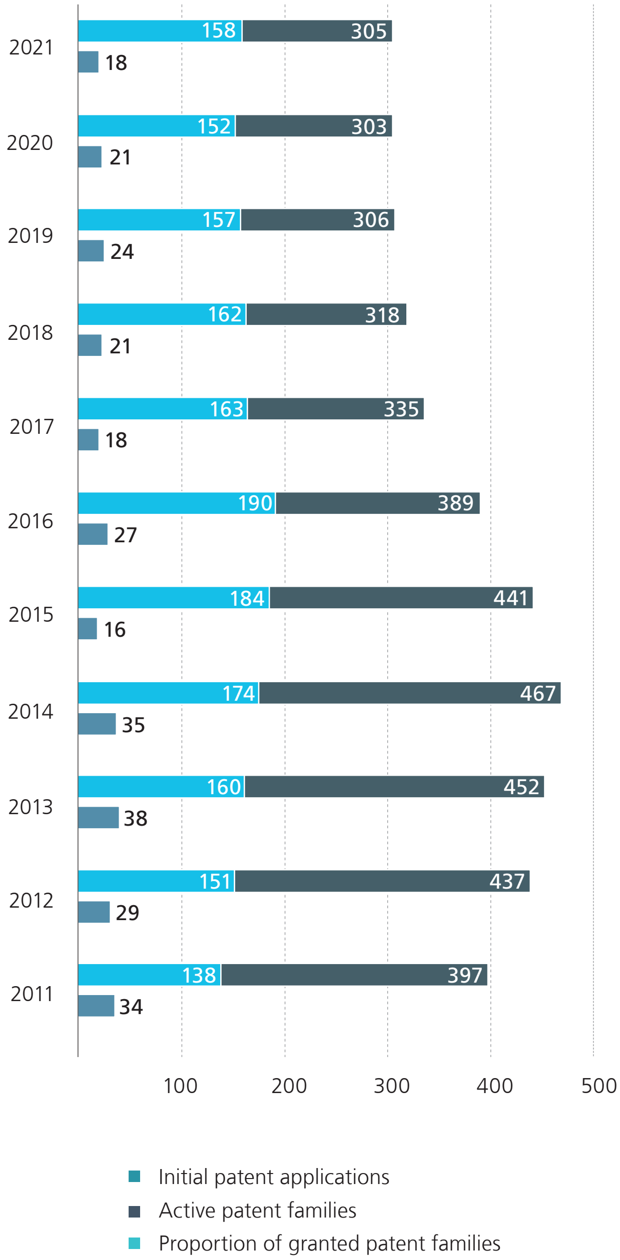
Income in Million Euros**



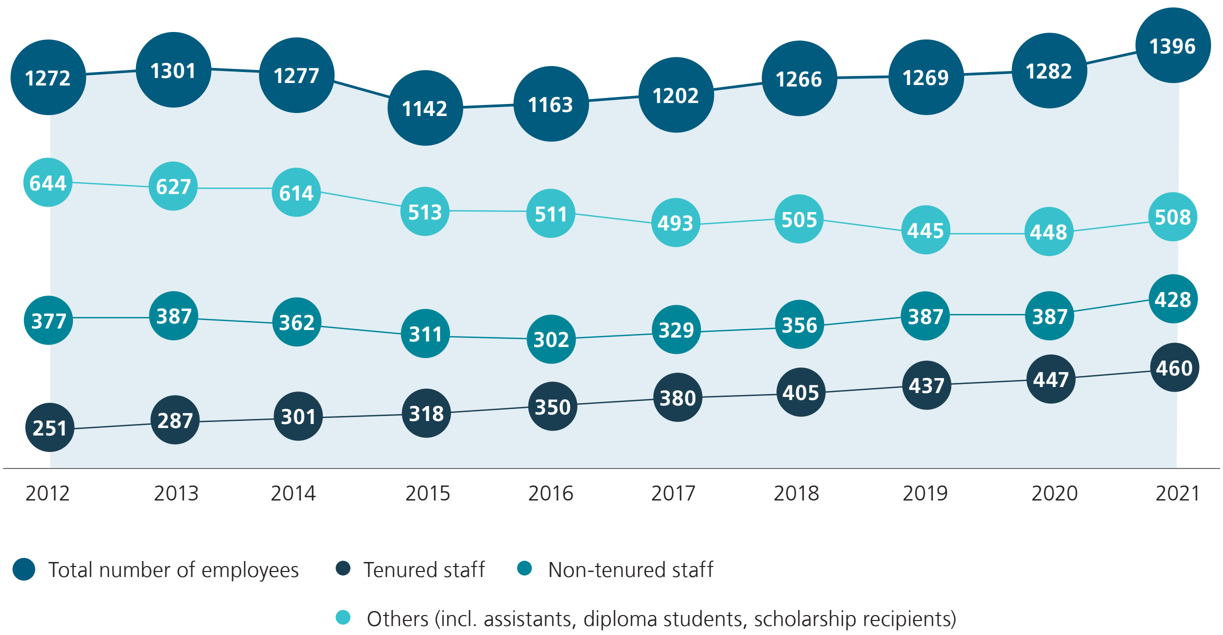
Expenditure in Million Euros**

* Preliminary ** Without investments – the total budget 2021 (incl. investments) totalled 118.1 million euros.

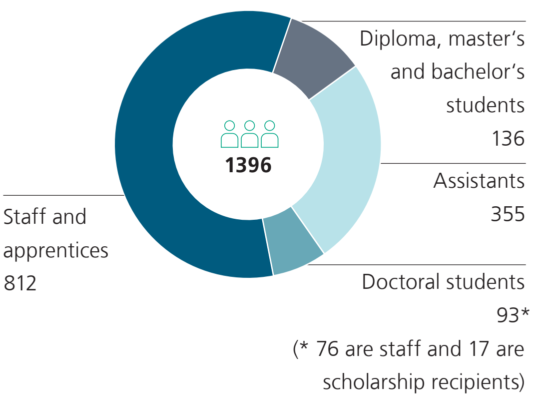
Patents



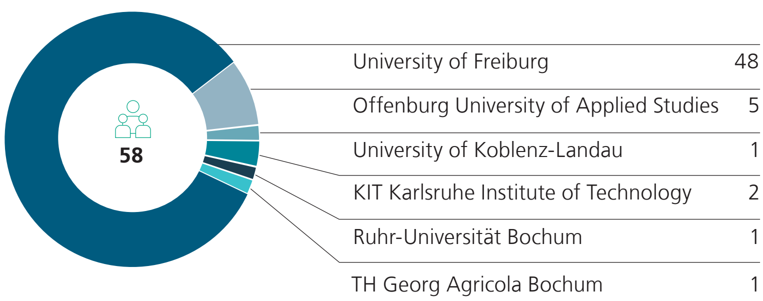
Personnel



Personnel in 2021



Lecture Courses and Seminars



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

Profile

Goal

The Fraunhofer Institute for Solar Energy Systems ISE, which was founded in Freiburg, Germany, in 1981, is the largest solar energy research institute in Europe, currently with a staff of 1 400. Our goal is to contribute with our research to preserving our planet and to protecting the basis of existence for current and future generations. We promote an energy supply system which is based on renewable energy sources and is sustainable, economic, safe and socially just. This goal is reflected in our 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 93 % of the Institute's funding originates from contracts for applied research, development and high-technology services. The total budget of the Institute amounted to 118.1 million euros in 2021.

Main building of Fraunhofer ISE in Freiburg.

Research Approach

Our aspiration is to develop concretely implementable, technical solutions which we make available to our industrial partners. 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 the interaction with politics and society, which we include in our work. Fraunhofer ISE addresses five market-oriented business areas (page 26 ff.). Our research ranges from materials research through component development to systems integration.

Activities

Fraunhofer ISE benefits from its excellent technical infrastructure. A laboratory floor area of 20 900 m² – including a clean-room area of 1 070 m² – and extremely modern equipment and facilities form the basis for our competence in research and development. This infrastructure encompasses eight R&D Centers and four production-relevant Technology Evaluation Centers (pages 44/45). The Institute also offers testing and certification services in its seven test and calibration laboratories that are accredited according to DIN EN ISO 17025:2018. On this basis, we operate as a reliable partner and implement R&D projects at the different levels of a technological life cycle – just as required by the individual contracts, demands and levels of maturity.

Our activities encompass:

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

Cooperation

Institute premises of the Fraunhofer Center for Silicon Photovoltaics CSP in Halle.

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

The Fraunhofer Center for Silicon Photovoltaics CSP in Halle is operated by Fraunhofer ISE jointly with the Fraunhofer Institute for Microstructure of Materials and Systems IMWS. The work of Fraunhofer ISE there focuses on crystallization and wafering of semiconductors, as well as recycling.

At the international level, the Institute participates directly in a collaboration in South America, namely 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 being its main topics.

Cooperation with Universities

Fraunhofer ISE places great value on educating future scientists. 48 employees teach at universities, there are about 230 B.Sc., M.Sc. and Ph.D students at the Institute and it cooperates directly with 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 basis makes INATECH unique in the research landscape and allows it to cover the complete spectrum from fundamental research through to industrial application. This cooperation is complemented by the "Sustainability Center Freiburg", which promotes networking with sustainably 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 Freiburg University. For example, we were able to contribute with our expertise on photovoltaics 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 on organic photovoltaics are located. Similarly, we have a tradition of cooperating closely with the Faculties of Physics, the Environment and Natural Resources, and 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 enterprises, organizations and research institutes around the world. The Institute is well connected at the national and the international levels within research and professional associations.

Cooperation within the Fraunhofer-Gesellschaft

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

Groups and Strategic Research Fields

The Fraunhofer Institutes work together within competence-oriented Groups. Fraunhofer ISE is a member, together with four other Institutes, of the Fraunhofer Group for Energy Technology and Climate Protection, which was founded in January 2021. Prof. Hans-Martin Henning is the Speaker for this Group. In addition, Fraunhofer ISE is a guest member of the Fraunhofer MATERIALS Group addressing Materials and Components.

The Fraunhofer-Gesellschaft also 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 Research Field of "Resource Efficiency and Climate Technologies". Prof. Christopher Hebling, Head of Division for Hydrogen Technologies at Fraunhofer ISE, and Prof. Mario Ragwitz from the Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG are the Speakers responsible for the Research Field of "Hydrogen Technologies".

Fraunhofer Alliances for Leading Markets

Parallel to scientific excellence, excellent transfer of results to the economic sector and society is also a focus of applications-oriented research. In this context, the Fraunhofer-Gesellschaft has defined eight leading markets since 2020 which are primarily addressed by the Fraunhofer Alliances.

Fraunhofer ISE is not only one of currently 20 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 (SysWasser) 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-Gesellschaft Initiative, "Morgenstadt – City of the Future".

Prizes and Awards

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
Winners of the Science4Life Energy Cup, business concept "PV2plus", Science4Life, 02.03.2021

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
3rd Prize for excellent innovation performance in the Innovation Competition of the Associations, BDE, BDSV and VDM, "PV2plus", BDE, BDSV, VDM, 18.03.2021

Dr. Henning Helmers, Dr. Oliver Höhn, Dr. David Lackner et al.
Best Paper Award, "Non-Uniform Illumination Impacts on O-Band InGaAsP and Metamorphic GaInAs Photonic Power Converters", OWPT Conference, 19. – 22.04.2021

Dr. Tim Niewelt
SiliconPV Award, Paper "State-of-the-Art Reassessment of the Intrinsic Bulk Recombination in Crystalline Silicon", SiliconPV 2021, 19. – 23.04.2021

Andreas Wessels
3rd Prize, Poster Award, "Farbige gebäudeintegrierte solarthermische Kollektoren mit hohem Wirkungsgrad" (Colored Building-Integrated Solar Thermal Collectors with High Efficiency), Solarthermie-Symposium, 27. – 30.04.2021

Dr.-Ing. Sebastian-Johannes Ernst
Science Prize of the Coburg Convent for a doctoral thesis "Development and Characterization of Advanced Materials for Heat Transformation Applications", Coburger Convent Akademie, May 2021

Cornelius Armbruster
2nd Prize, Poster Award, "Untersuchung verschattungsoptimierter Halbzellenmodule mit einlaminierter Leistungselektronik (LE) für das MPP-Tracking auf Substring-Ebene" (Investigation of Shading-Optimized Half-Cell Modules with Power Electronics Integrated into the Laminate for MPP-Tracking at the Sub-String Level), 36. Symposium Photovoltaische Solarenergie 2021, 25.05.2021

Rebekka Denninger
3rd Prize, Poster Award, "Bereitstellung der Regelleistung durch netzbildende Wechselrichter am Beispiel der Systemauftrennung vom 08.01.2021" (Provision of Control Power by Grid-Forming Inverters Illustrated by the System Separation of 08.01.2021), 36. Symposium Photovoltaische Solarenergie 2021, 25.05.2021

Dr. Jörg Schube
UMSICHT Science Prize, scientific doctoral thesis category "Metallization of Silicon Solar Cells with Passivating Contacts" at the University of Freiburg, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, 24.06.2021

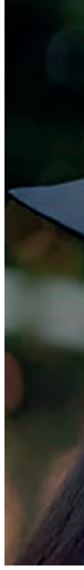
Dr. Markus Feifel
Gips-Schüle Young Scientists' Prize, Certificate of Honor in the Category of Technical Sciences, doctoral thesis, "Hocheffiziente III-V-Mehrfachsolarzellen auf Silicium" (High-Efficiency III-V Multi-Junction Solar Cells on Silicon" at the University of Constance, Gips-Schüle Foundation, 27.07.2021

David Fischer, Arne Groß, Antonia Lenders
Hans-Jürgen Appelrath Best Paper Award, conference paper "Comparison of Short-Term Electrical Load Forecasting Methods for Different Building Types",10th DACH+ Conference on Energy Informatics, 16.09.2021

Dr. Alexander Bett
Eva-Mayr-Stihl Young Scientists' Prize 2021 of the University of Freiburg, doctoral thesis, "Perovskite Silicon Tandem Solar Cells – Two-Terminal Perovskite Silicon Tandem Solar Cells Using Optimized n-i-p Perovskite Solar Cells", University of Freiburg, 20.10.2021

Dr. Stefan Henninger, Dr. Saskia Kühnhold-Pospischil, Nicole Nierlich, Julia Packetat
1st Prize, BestChance Award 2021, "Concept to prevent and intervene against sexual harassment at the workplace", Fraunhofer-Gesellschaft, 24.11.2021

Dr. Harry Wirth
Fraunhofer-Taler
Outstanding commitment in maintaining "Facts on Photovoltaics", Fraunhofer-Gesellschaft, 15.12.2021



Doctoral Theses

Puzant Baliozian
"Development and Characterization of Bifacial p-Type Silicon Shingle Solar Cells with Edge Passivation"
University of Freiburg, 2021

Andreas Beinert
"Thermomechanical Design Rules for the Development of Photovoltaic Modules"
Karlsruhe Institute of Technology (KIT), 2021

Christian Bischoff
"Herstellung und Charakterisierung von Zink-Ionen-Batteriezellen für stationäre Anwendungen"
(Production and Characterization of Zinc-Ion Battery Cells for Stationary Applications)
University of Freiburg, 2021

Nicolas Carbonare
"Occupant-Centered Control Strategies for Decentralized Residential Ventilation"
Karlsruhe Institute of Technology (KIT), 2021

Angela De Rose
"Evaluation of Solder Joints on Aluminum Surfaces for the Interconnection of Silicon Solar Cells"
University of Rostock, 2021

Lena Emmer (born Mohr)
"Strömungs- und Reaktionsmodellierung sowie deren experimentelle Untersuchung in einem chemischen Prozess-becken für die Herstellung von Silizium-Solarzellen" (Fluid Dynamic and Reaction Modeling and their Experimental Investigation in a Chemical Processing Tank for the Production of Silicon Solar Cells)
University of Freiburg, 2021

Dorian Guzman Razo
"An Adaptive Model of PV Power Output"
University of Freiburg, 2021

Thibaud Hatt
"Electroplating Based on Self-Passivated Aluminium Masking for Metallization of Silicon Heterojunction Solar Cells"
University of Freiburg, 2021

Ulrike Heitmann
"Development of a ZnO-Based Transparent Conductive Adhesive for the Application in III-V/Silicon Tandem Solar Cells"
University of Freiburg, 2021

David Hermann
"Characterization of Metallization-Induced Recombination Losses of Screen-Printed Silicon Solar Cells"
University of Freiburg, 2021

Clarissa Hofmann
"Control of Upconversion Luminescence for Photovoltaics Using Photonic Structures"
University of Karlsruhe, 2021

Jonas Huyeng
"Printable Boron Dopant Sources for Silicon Photovoltaics"
University of Freiburg, 2021

Robin Lang
"Defekte in III-V-Halbleitermaterialien des GaInAsP-Systems"
(Defects in III-V Semiconductor Materials in the GaInAsP System)
University of Constance, 2021

Eric Laurenz
"Frequency Response Analysis of Heat and Mass Transfer in Adsorbent Composites and Simplified Performance Estimation for Heat Transformation Applications"
Technical University of Hamburg, 2021

Christoph Luderer
"Transport Properties of Thin-Film Passivating Contacts for Silicon Solar Cells"
University of Freiburg, 2021

Juan Franciso Martinez Sanchez
"Development of Hybrid Concentrator/Flat-Plate Photovoltaic Technology to Reach the Highest Energy Yield"
University of Freiburg, 2021

Mohammad Hassan Norouzi
"Plasma-Based Multifunctional Surface Modification and Laser Doping Technologies for Bifacial PERL/PERC c-Si Solar Cells with Selective Emitter"
University of Freiburg, 2021

Daniel Ourinson
"Advancement and Evaluation of the Firing Process for Silicon Solar Cells with High-Temperature Pastes"
University of Freiburg, 2021

Lazhar Rachdi
"Characterization of Plasmas for the Deposition of Thin Films for Crystalline Silicon Solar Cells"
University of Freiburg, 2021

Kasimir Reichmuth
"Effekte in der akkuraten I-V-Charakterisierung von Mehrfachsolarzellen bei einer Sonne und bei hohen Bestrahlungsstärken" (Effects in the Accurate I-V Characterization of Multi-Junction Solar Cells at One Sun and High Irradiation Intensities)
University of Freiburg, 2021

Ahmed Ismail Ridoy
"Maskless Dry Texturing Methods for Crystalline Silicon Solar Cells"
Karlsruhe Institute of Technology (KIT), 2021

Shahab Rohani
"Reducing the Water Footprint of Concentrated Solar Power Plants. Techno-Economic Assessment of Water Saving Solutions for CSP Plants"
University of Freiburg, 2021

Waldemar Schreiber
"Elektrochemisches Ätzen und Tempern mesoporöser Germaniumschichten für die Verwendung als ablösbare Epitaxievorlage" (Electrochemical Etching and Tempering of Mesoporous Germanium Layers for Application as Separable Epitaxial Templates)
University of Osnabrück, 2021

Christian Sonner
"Generische Auslegung eines Sorptionsbettes zur Aufnahme von natürlichen Kältemitteln bei unterschiedlichen Leckagen" (Generic Design of a Sorption Bed to Absorb Natural Refrigerants for Different Leaks)
University of Freiburg, 2020

Laura Stevens
"Strukturierte Sol-Gel-Antireflexoberflächen zur Optimierung von Lichteinkopplung in der Silicium-Photovoltaik" (Structured Sol-Gel Anti-Reflective Surfaces to Optimize Light Coupling in Silicon Photovoltaics)
University of Freiburg, 2021

Sebastian Tepner
"Contribution to the Understanding of Screen Printing and its Implication for the PV Industry"
University of Freiburg, 2021

Lukas Wagner
"Perovskite Photovoltaic Modules with a Very Low CO_2-eq Footprint: The in situ Technology"
University of Freiburg, 2021

Julian Weber
"Lokale Laserdiffusion zur Herstellung hocheffizienter Siliziumsolarzellen" (Local Laser Diffusion to Produce High-Efficiency Silicon Solar Cells)
University of Freiburg, 2021

40 Years of Research for the Energy Transition

"In Baden-Württemberg we are really proud that ISE is located here."

Permanent Secretary, Michael Kleiner
Ministerium für Wirtschaft, Arbeit und Tourismus Baden-Württemberg (Ministry of Economic Affairs, Labor and Housing), Stuttgart

"We must reduce our fossil fuel consumption more quickly at the national, regional and municipal levels."

Christine Buchheit
Mayor of the City of Freiburg

Fraunhofer ISE, the largest European solar research institute, celebrated its 40th anniversary in 2021. It owes its establishment to the solar pioneer and founding Institute Director, Prof. Adolf Goetzberger, whose clear goal – even then – was to replace fossil fuels by renewable energy. Today, this idea has a widely known name: the energy transition.

Over the past years, Fraunhofer ISE logged up many minor and major successes, milestones and technological breakthroughs. To name examples, these included the construction of the first self-sufficient solar house in 1992, the opening of the Photovoltaic Technology Evaluation Center in 2006, the successful transfer of the HERIC® topology for inverters to industry in 2003 or the solar hydrogen filling station in 2012. The PV technologies developed at the Institute not only set numerous efficiency records, such as that for multicrystalline silicon solar cells (22.3 %), silicon solar cells contacted on both surfaces with TOPCon technology (26.0 %), III-V silicon tandem solar cells (35.9 %) and a III-V four-junction concentrator cell (46.1 %) but they also found their way into the industry. The expectation that knowledge would be transferred from the laboratory into practice is reflected by the broad spectrum of research: As the transformation of the energy supply to renewable energy sources does not end with energy conversion, our scientists also address sustainable energy distribution, storage and utilization.

In addition to technological questions, aspects concerning sustainable circular economy, resource and cost efficiency but also political and holistic social boundary conditions are becoming



increasingly urgent. For instance, the recently updated study from Fraunhofer ISE on "Paths to a Climate-Neutral Energy System – The German Energy Transition in its Social Context" demonstrated the large effect of social behavior on the effort and costs needed to change the energy system.

But why are there not more solar panels on roofs? Do we need more technological pilot projects? Or even mandatory solar installation? And how can this demand be reconciled in turn with basic democratic principles? These questions were debated by representatives from research, politics and the economy during a panel discussion on "Sustainable research for the energy transition – and for the generations after us" as part of the 40th anniversary celebration. The focus was on the question of acceptance by the population.

Dr. Sebastian Gölz, a sociologist at Fraunhofer ISE, pointed out that in this context, acceptance in the sense of simple "tolerance" is not sufficient. At the end of the day, according to Gölz, it is a matter of generating awareness and enthusiasm for the topic – a clear mandate for more education e.g. about the electrification of heating and mobility or the fact that PV electricity is not more expensive for the population than electricity from fossil fuels. Dr. Britta Buchholz from Hitachi Energy added that there is often a lack of technical knowledge in the population, particularly concerning the building and the transport sectors. The Institute Director, Prof. Hans-Martin Henning, recommended more involvement of citizens, particularly at the municipal and neighborhood levels.

The panelists came to the conclusion that the technologies are ready for adoption in many areas but their implementation is proceeding too slowly. Walburga Hemetsberger from SolarPower Europe thus demanded: "Rapid upscaling must be supported by politics." Apart from challenges to politicians, however, it is essential to engage society as a whole more strongly. "After all, every individual can make their own contribution", concluded the Institute Director, Prof. Andreas Bett.

Photos from left to right:

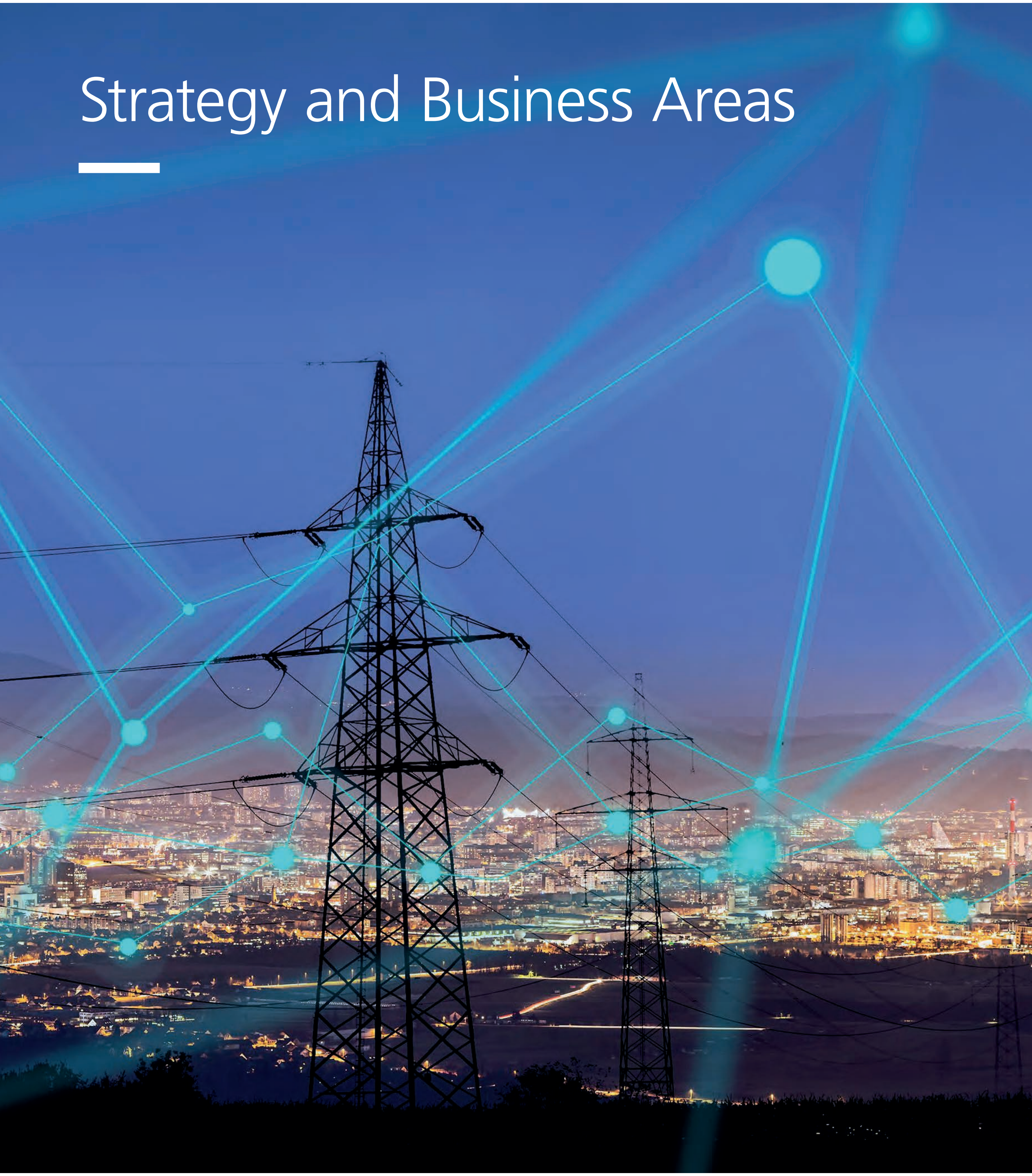
Panel discussion hosted by Fraunhofer ISE. From left to right: Axel Wagner (compere), Dr. Britta Buchholz (Hitachi Energy), Prof. Hans-Martin Henning, Walburga Hemetsberger (SolarPower Europe), Dr. Sebastian Gölz, Prof. Andreas Bett.

Institute Directors, Prof. Andreas Bett (left) and Prof. Hans- Martin Henning (right) with the former Institute Directors, Prof. Joachim Luther (center) and Prof. Eicke R. Weber and the former Institute Deputy Director, Prof. Volker Wittwer (second from the left).

140 guests accepted the invitation to the event celebrating the Institute's 40th anniversary.

The evening reception offered an opportunity for discussion and networking.

Strategy and Business Areas



Our newsletter offers regular updates on our research highlights.

Contents

Quo vadis, Energy Transition?

A conversation with the Institute Directors, Prof. Hans-Martin Henning and Prof. Andreas Bett

The European Union and the new German government have set more ambitious goals for CO_2 neutrality. In your view, what is the current status of the energy transition?

Bett: "The European Green Deal and the German Federal elections will certainly have a major impact on the further course of the energy transition. An adapted industrial policy must now be oriented towards climate policy requirements, transformation processes must be significantly accelerated and new regulations must be introduced with increased emphasis. A CO_2 reduction of 65 % in German emissions by 2030 can only be achieved if that happens. In addition, industrial policies must be adapted to reflect the climate-relevant demands. The government must really take action now."

Henning: "Reducing bureaucracy and speeding up approval processes seem particularly important to me. Overcomplex rules and regulations create unnecessary hurdles, which often result from a thicket of guidelines that have grown over time. I hope that the new government can reorder and speed things up here."

Fraunhofer ISE supports industry on its path toward climate neutrality with research and development projects. What do the companies need for success in this area?

Henning: "In many cases, commercial enterprises are much more advanced than politics. More and more companies are actively developing their own plants to become climate-neutral. But they need a clear political message that this will be supported and sustained. Reliable, transparent political boundary conditions are decisive for the economy. Here and there, financial support is still needed for initial market development. However, the highest priority is to have consistent, long-term regulations. An important example would be harmonized and yet more effective CO_2 pricing systems."

You have published various studies on possible transformation routes toward a climate-neutral energy system. How open is the energy transition still for different technologies?

Henning: "Technology openness is very important for research and development but we only have a limited timeframe to achieve the climate goals. Particularly with regard to the necessary infrastructure – like electricity grids, gas pipelines or charging stations – we will need years, if not decades, from planning to the final implementation. The course must be set and decisions made now, so that the economic sector can plan its future."

Which main R&D topics result for Fraunhofer ISE from these considerations?

Bett: "There is still a lot to do, both concerning systemic questions and also at the component level – even if the essential technologies for the energy transition are already available today. Our research and development work addresses the evolutionary further development of these technologies, e.g. to optimize production with regard to efficiency and closed resource cycles, as well as lengthening the service life of materials and components. Our vision is to implement the energy transition sustainably."

Henning: "The energy system of the future will need many millions of new converters, distribution systems, storage components, etc. That presents a great challenge, primarily because of the materials that are needed. We want to work on providing comprehensively sustainable technologies, processes and system solutions."

You mentioned the sustainability of production. What effect will that have?

Bett: "Initially, it is a matter of analyzing both product life cycles and production processes in great detail. This includes investigating the materials used, their provenance and their processing. In addition, it will involve establishing a circular

Prof. Andreas Bett.

Prof. Hans-Martin-Henning.

economy, reusing components and recycling materials. In this context, we are campaigning for relocation of all aspects of the PV production value chain to Europe. For example, this would reduce the need for transport, which has both ecological and economic advantages. A further aspect is greater application of digital processes to minimize wastage."

In 2021, Fraunhofer ISE officially opened its new Center for High Efficiency Solar Cells. What expectations are associated with it?

Bett: "We are advancing research on tandem solar cells there. In this approach, different semiconductor materials are stacked on top of each other to achieve higher efficiency. Higher efficiency means lower consumption of materials and a reduced demand for installation area. In the new center, we are intensifying these activities, particularly concerning tandem solar cells on silicon. We assume that it still needs five to ten years of intensive R&D work before tandem solar cells can become a mainstream product."

Which further challenges do you see concerning infrastructure and systems?

Henning: "A central challenge is the development of a grid infrastructure which can accommodate large quantities of renewably generated electricity and still guarantee high grid quality and security of supply. The development of grid-forming converter systems plays a decisive role in this process. And there is an increasing focus on electricity storage units. We have developed comprehensive competence on batteries – from the materials, through the cells, up to systems – and are further expanding our technical infrastructure and capacity. We are concentrating particularly on large, stationary storage systems, e.g. in neighborhoods or the sites of power plants and industrial zones. We observe a general trend of industry increasingly asking for systemic approaches to make their sites and production processes climate-neutral. For example, we are extending our extensive experience with heat pumps in the building sector to encompass large heat pumps for industry and heating networks and have started the first research projects in this direction, also in cooperation with other Fraunhofer Institutes. Our goal is to develop complete solutions for commercial enterprises and real estate."

How does this affect cooperation with your clients and partners?

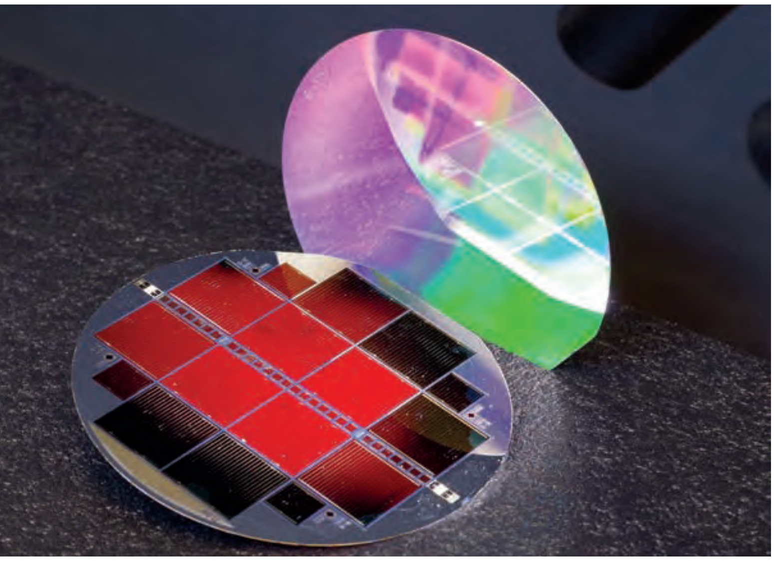
Bett: "Since the foundation of Fraunhofer ISE, we have pursued many technological approaches over a wide spectrum and have maintained an integrated view of the energy transition. Our clients appreciate this, as it allows us to bring together different areas of competence and create synergistic effects. Where we cannot do this within Fraunhofer ISE, we use our association with other Fraunhofer Institutes. We aim to be a reliable partner for the industry and keep its needs in focus. Maintaining relationships with satisfied clients over many years is also one aspect of our sustainability vision."

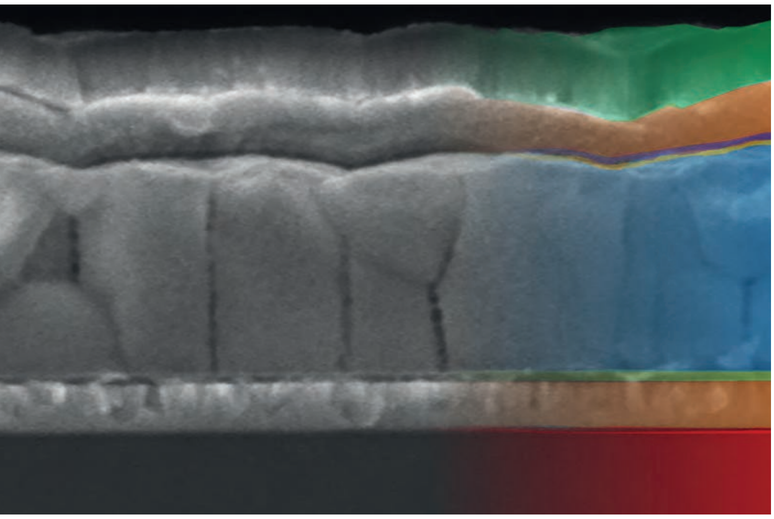
Politics and industry have focused more strongly on hydrogen in recent years. Fraunhofer ISE advises the Fraunhofer-Gesellschaft and the German Federal government on this topic. Which further development do you foresee?

Henning: "Hydrogen and molecules produced from hydrogen, such as methanol, OME* or ammonia, will develop into a multi-billion industry. Unlike many other energy applications, the fossil fuels used today in shipping and aviation and as chemical raw materials for industry cannot be replaced directly by electricity. Fraunhofer ISE thus opted early for hydrogen, so that we have already built up a broad R&D portfolio for hydrogen production and its conversion to electricity in fuel cells, as well as its conversion to a great variety of other molecules. We are noticing very strongly growing interest from politics and the industry on this work. We will continue to meet their expectations."

* OME (oxymethylene ethers) can be synthesized from hydrogen and CO_2 and replace fossil fuels.

Tandem Photovoltaics – the Road to Higher Conversion Efficiency





Solar cells which are made of only one semiconductor material, such as silicon, dominate today's photovoltaic market. However, their efficiency is limited for physical reasons to less than 30 % – a value which represents a real limit when the impressive efficiency increase for industrially produced cells of 0.5 % per year is taken into account. Thus, a central goal for photovoltaics research is to develop tandem solar cells, in which two or more semiconductors with different energy bandgaps are used. Such tandem solar cells are already the standard for space applications but mass production for terrestrial applications has higher demands regarding manufacturing costs and upscaling. Many research groups at universities, research institutes and in the industry are thus currently addressing these topics.

Fraunhofer ISE plays a special role in this exciting field. On the one hand, we have been successfully developing multi-junction solar cells of III-V semiconductors for space and concentrator PV applications for more than twenty years. This expertise, together with our excellent silicon solar cell technology (page 58), has helped us to achieve very good results also for silicon-based tandem solar cells such as III-V on silicon or perovskite on silicon. Our new Center for High Efficiency Solar Cells (pages 50/51) offers excellent experimental facilities for this work. On the other hand, meticulous characterization and calibration of complex tandem solar cells also have a long tradition at the Institute – a service, which is regularly used by other leading research groups.

Top:
III-V silicon tandem solar cell with an efficiency of 35.9 %.

Bottom:
Scanning electron microscope image of the cross-section through a perovskite-silicon tandem solar cell.

In addition to this comprehensive competence regarding solar cells, Fraunhofer ISE is able to cover the entire technological bandwidth from materials development up to integration into systems. After all, successful development of tandem solar cells is only the first step in implementing tandem photovoltaics: III-V silicon and perovskite-silicon tandem solar cells indeed already achieve impressive efficiency in the laboratory, but how are these new cell types to be contacted in industrially relevant processes, for example? And how can the cells be integrated reliably and durably into a module? This is where the technology evaluation centers at Fraunhofer ISE, PV-TEC and Module-TEC, play their part.

Perovskite semiconductors cannot withstand the high temperatures that are applied to process silver contacts. In PV-TEC, we are thus developing new contacting technology (page 62), which operates at low processing temperatures and has a particularly low silver consumption.

A central precondition for a PV technology to become successful is a long service life. Perovskite semiconductors are known to be sensitive to moisture. Thus, we have developed special encapsulation technology in Module-TEC, which enables perovskite-silicon tandem modules to pass the demanding damp heat test and the other prescribed IEC tests*. Connection of these sensitive cells also poses great challenges to the industry, for which we at Fraunhofer ISE are preparing solutions that will support our development partners in this dynamic technological area.

Top:
FlexTrail contacting of solar cells with a particularly low silver consumption (left); scanning electron microscope image of a FlexTrail contact finger (right).

Bottom:
Structured connectors for serial connection of silicon-perovskite solar cells using electrically conductive adhesives (ECA).

* Tests of module reliability defined in standards of the International Electrotechnical Commission IEC.

Silicon Photovoltaics

"PV modules of silicon solar cells are an important pillar of the energy transition. Our research is targeted toward further improving their performance."

Dr. Ralf Preu,
Prof. Stefan Glunz
Heads of Division
Silicon Photovoltaics

Market Position

More than 90 % of all solar cells around the world are manufactured of crystalline silicon. The keys to this dominant position are their high efficiency, a cost-effective mass-production process and a product lifetime of several decades. The cell efficiency is decisive to further reduce the levelized cost of electricity and utilize resources more efficiently, so it is at the focus of our activities. Fraunhofer ISE supports the research and development by manufacturers of materials, modules and production equipment with its globally unique R&D infrastructure with laboratories and technological centers occupying more than 3000 m², for example in our industrially relevant technological centers, PV-TEC and SiM-TEC and the recently opened Center for High Efficiency Solar Cells. The scientific and technological competence of our more than 300 staff members ranges from silicon materials, through solar cells and modules, up to systems. Thus, our cooperation partners have access not only to individual technologies, but to the entire value chain when they work together with us.

Facts and Figures

Total staff	313
Journal articles and contributions to books	60
Lectures and conference papers	73
Newly granted patents	10

Selected Projects in 2021

- INNOMET – Development of Innovative Printing Technologies for Fine Line Metallization of Si Solar Cells
- Reassessment of the Intrinsic Bulk Recombination in Crystalline Silicon
- Design Rules for High-Efficiency both-sides-contacted Silicon Solar Cells with Balanced Charge Carrier Transport and Recombination Losses
- PrEsto – Perovskite Silicon Tandem Solar Cells: Development of Scalable Process Technologies

More information on these and further projects

More information on this business area

III-V and Concentrator Photovoltaics

"Concentrator photovoltaics makes the highest PV efficiency feasible. That is why we want to lead this technology to economic success."

Dr. Frank Dimroth
Head of Department
III-V and Concentrator Photovoltaics

Market Position

The greater the expectations of society on photovoltaics, the more important it becomes to minimize its land use, increase energy conversion efficiency and develop sustainable products. Multi-junction solar cells of III-V semiconductors have already demonstrated that efficiency of 47 % is possible with concentrated sunlight. The III-V cells benefit from high intensities and are used for sunlight that is concentrated about 1 000 times.

However, even classic silicon can profit from moderate concentration. To this purpose, we develop special solar cells which separate the charge carriers efficiently despite high light intensity and apply tandem structures of III-V semiconductors combined with germanium or silicon. In addition, we develop optical components (Fresnel lenses and reflectors) for concentrator modules and construct prototypes in our Concentrator Technology Evaluation Center (Con-TEC). Hybrid concentrator modules achieve peak performance of up to 350 W/m². Our goal is to reduce costs further by applying optical micro-components and miniaturized cells and to lead concentrator technology to commercial maturity.

Facts and Figures

Total staff	46
Journal articles and contributions to books	15
Lectures and conference papers	26
Newly granted patents	2

Selected Projects in 2021

50 Prozent/50 Percent – Monolithic III-V Multi-Junction Solar Cells with more than 50 % Efficiency under Concentrated Irradiation

QuintuMod – Development of a Low-Cost and High-Efficiency Solar Module using a Solar Cell with Five pn Junctions

PoTaSi – Demonstration of the Potential of Monolithic Tandem Solar Cells made of III-V Semiconductors and Silicon

micro-CPV – Development of a Highly Concentrating CPV Module Based on Modern Micro-Production Technology

H2Demo – Development of Demonstrators for Direct Solar Water Splitting

AIIR-Power Joint Project: Development of AI Techniques to Optimize Opto-Electronic Components and their Application for Telekom Wavelengths

More information on these and further projects

More information on this business area

Perovskite and Organic Photovoltaics

"The progress we have achieved brings us appreciably closer to opening up new application areas."

Dr. Uli Würfel
Head of Department
Perovskite and Organic
Photovoltaics

Market Position

Very high efficiency has already been achieved with perovskite solar cells and further increases are to be expected in the near future. However, the record efficiency values so far were achieved with cell stacks which are less durable and also do not present a realistic option for upscaling. For this reason, Fraunhofer ISE is developing cell concepts that ensure both sufficient long-term stability and also upscaling potential, and additionally make low manufacturing costs feasible.

The efficiency of organic photovoltaics was significantly increased by applying novel absorber materials and again, future improvement is also anticipated here. At Fraunhofer ISE, we are working on transferring these improvements to the roll-to-roll production of flexible solar modules. First applications are already being found in the Internet of Things (IoT) sector. Further improvements in efficiency and durability should open up applications in building-integrated photovoltaics and agri-photovoltaics in future.

Facts and Figures

Total staff	35
Journal articles and contributions to books	15
Lectures and conference papers	17

Selected Projects in 2021

- ORGANAUT – Organic Photovoltaics for Autonomous Linked Sensors and Internet of Things
- UNIQUE – Carbon Based Perovskite Solar Cells with UNI-Directional Electron Bulk Transport: in the QUEst of a Short Time to Market
- PeroTec – Upscalable Perovskite Technology
- APOLO – SmArt Designed Full Printed Flexible RObust Efficient Organic HaLide PerOvskite solar cells
- ADAPT – Adaptation to Climate Change with Organic PV for Agri-Photovoltaics

More information on these and further projects

More information on this business area

Photovoltaic Modules and Power Plants

"Many years of massive PV expansion lie ahead of us but land usage can be limited by integration."

Dr. Harry Wirth
Head of Division
Photovoltaics, Modules
and Power Plants

Market Position

More ambitious climatic goals will further accelerate the expansion of photovoltaics. Depending on the scenario, between 12 and 20 GW_p per year are needed in Germany alone. Enormous potential areas can become available by integrating PV modules in agricultural and inland water areas, building and vehicle envelopes, parking areas and transport routes. These applications demand highly efficient modules with a product design that creates synergistic opportunities and encourages widespread acceptance.

Larger wafer formats and the division of solar cells demands a rapid transition to multi-wire or shingle connection by the module manufacturers. We can reproduce all important connection technologies in industrial formats in our Module Technology Evaluation Center. The increasing dimensions of module formats with power exceeding 500 W_p and the innovation speed place highest demands on characterization and reliability testing. Our accredited calibration laboratory offers highest accuracy, with a measurement tolerance of 1.1 %.

Facts and Figures

Total staff	201
Journal articles and contributions to books	25
Lectures and conference papers	43
Newly granted patent	1

Selected Projects in 2021

- IEA PVPS Task 13 – Performance, Operation and Reliability of Photovoltaic Systems
- APV Obstbau – Agri-Photovoltaics as Resilience Concept for Adaptation to Climate Change in Orcharding
- KoMoGER – Competitive Modules "Made in Germany"
- PVwins – Development of Wall-Integrated PV Elements for Noise Protection
- BALDACHIN – Development of an Innovative Solar Roof Element – Cost-Effective, Attractive and Easy to Install
- OptOM – Cost-Optimized Operation Management of PV Plants over their Economic Lifetime
- Shirkan – Matrix Shingle PV Module – Robust, Cost-Effective, Aesthetic and Highly Efficient
- SOLREV – Solar Resources and Predictions for the Grid and Market Integration of Solar Energy

More information on these and further projects

More information on this business area

Energy Efficient Buildings

"The heating transformation presents a challenge particularly for the existing building stock. A transition from fossil fuels to electricity as the energy form is a central part of the solution."

Dr. Peter Schossig
Head of Division
Energy Efficient Buildings

Market Position

The building sector is the only one which did not meet the German climate-protection goals in 2020. There are many causes: A large range of actors, a shortage of tradespeople, particularly in the plumbing, heating and air-conditioning trades, and relatively high CO_2 prevention costs all play a role. The challenge consists of providing solutions to these problems: decarbonized heating technologies, transformation concepts for the housing economy and industrial enterprises, creation of new capacity in the trades and the changeover to green district heating.

The current discussions about suitable refrigerants will also be relevant to heat pumps in the higher power classes. New R&D capacity is being created by establishing KETEC, a new research platform for cooling technology, in which we are participating. In association with further Fraunhofer Institutes, the topic of heating has been added to the portfolio of the Fraunhofer Cluster of Excellence on Integrated Energy Systems (CINES), particularly to provide scientific support to the transformation of district heating.

Facts and Figures

Total staff	158
Journal articles and contributions to books	24
Lectures and conference papers	24
Newly granted patents	5

Selected Projects in 2021

- Smart Quarter Durlach – Group Project: EnEff:Stadt – KA-Durlach: Smart Quarter Karlsruhe-Durlach
- SCOPE – Project Data Environment and Modeling of Multifunctional Building Products with Focus on the Building Envelope
- DiBesAnSHK – Digitalization of Initial Appraisal and Quote Preparation in the Plumbing, Heating and Cooling Trades
- LC 150 – Development of a Heat Pump Module Applying Smaller Amounts of Propane as the Refrigerant
- Farbkollektor – Concepts for Architecturally Adapted Collectors for the Existing Building Stock and New Buildings
- Reallabor Großwärmepumpen – Living Laboratories for the Energy Transformation
- HEAVEN – Modulating Brine Heat Pump with Multiple-Source System and Decentralized Ventilation Equipment
- WAMS – Heat Pumps – Acoustics and Multi-Source Systems

More information on these and further projects

More information on this business area

Solar Thermal Power Plants and Industrial Processes

"

Efficient, cost-effective and compact thermal storage units are central components for the thermal energy transition, sector coupling and the transformation of industry."

Dr. Peter Nitz
Head of Department
Solar Thermal Power Plants
and Industrial Processes

Market Position

High-temperature solar heat can be stored cost-effectively. It can then be used on-demand, at any time, to generate electricity in solar thermal power plants or to power industrial processes. Despite these advantages, the technology is not very common yet. With our research, we want to contribute to wider application by reducing the cost of solar heat and its storage. In future, different technologies will be combined to provide energy or heat in order to achieve the transformation to low-CO_2 industry. Together with efficiency measures and the use of waste heat, large-scale high-temperature heat pumps, for example, can provide industrial heat reliably. The combination of heat pumps – powered by electricity from renewable sources – and the use of solar thermal heat has the potential to provide heat entirely from renewables. Storage units for heat at high and low temperatures represent central components for such types of hybridization.

Besides the supply of energy, efficient use of resources is a central topic for the future. To achieve this, we are developing membrane-based processes for desalination to recover valuable fluids and materials from industrial wastewaters and to extract precious raw materials from geothermal brines.

Facts and Figures

Total staff	60
Journal articles and contributions to books	9
Lectures and conference papers	9
Newly granted patents	5

Selected Projects in 2021

- AVUSpro – Automated in situ Measurement of Soiling for Site Assessment and Operation of Solar Thermal Power Plants
- FENOPTHES – Development and Optimization of Filler Materials for Thermal Storage
- HelioGLOW – Development of Components for a Solar Thermal Tower Power Plant
- HelioSense – Development of an Innovative 3D-Laser-Soiling Scanner for Autonomous Application in Solar Thermal Power Plants
- KOKAP – Cost-Efficient Capsule Technologies for Phase Change Materials
- Modulus – Modular Power Transfer Station
- Optimus – Development, Optimization and Application of PCM Emulsions with High Thermal Storage Density

More information on these and further projects

More information on this business area

Hydrogen Technologies and Electrical Energy Storage

"Hydrogen is the energy-relevant declaration of independence from the fossil-fuel age and the climate crisis it has caused."

Prof. Christopher Hebling
Head of Division
Hydrogen Technologies and
Electrical Energy Storage

Market Position

The transformation to a decarbonized, global energy system is occurring via a mixture of locally used renewables and the generation and subsequent transport of sustainable fuels from sunny and windy regions. We are accompanying this process by preparing technological and system studies as well as economic evaluation, such as in the HySupply or HyPat projects. Furthermore, we are developing a deep understanding of the processes in the membrane-electrode assemblies (MEA) of PEM fuel cells or PEM electrolyzers by intensive characterization and modeling and are researching automated processes for their industrial production.

Batteries are rapidly gaining relevance in the expansion of fluctuating forms of renewable energy and, as highly efficient, mobile storage units, are the foundation of a successful transport transformation. We conduct research along the entire value chain from battery materials and cells, through battery systems technology and testing, to diverse applications of battery storage units.

Facts and Figures

Total staff	208
Journal articles and contributions to books	24
Lectures and conference papers	43
Newly granted patents	5

Selected Projects in 2021

- HyFab-BW – HyFab-Baden-Württemberg – Research Factory for Hydrogen and Fuel Cells, Part 2
- Prometheus – New Concept of a Proton Exchange Membrane Electrolysis Stack for Elevated Temperatures and Pressures
- StoRelH2 – Storage/Release H2 – Efficient and Cost-Effective Hydrogen Storage and Transport with Liquid Organic Hydrogen Carriers
- PLöPSS – Development of Passive Solutions to Inhibit Propagation in Stationary Storage Systems
- OrtOptZelle – Position-Dependent Compression of Battery Pouch Cells for Lifetime Optimization
- FLiBatt – Solid Lithium Batteries with Non-Woven Materials
- BetterBat – Evaluation of the Technical and Systemic Fit of Battery Technologies for Battery-Relevant Applications

More information on these and further projects

More information on this business area

Power Electronics, Grids and Smart Systems

"A renewable energy system demands a smart electricity grid with power electronic converters."

Prof. Christof Wittwer
Head of Division
Power Electronics, Grids
and Smart Systems

Market Position

In the business area for "Power Electronics, Grids and Intelligent Systems", we address innovative technologies to transform the electricity system. We offer studies on energy systems analysis to identify technological trends and cost-optimized transformation options for sustainable energy supply systems.

Due to the increasing coupling between the electricity, heat and mobility sectors and the associated electrification of the sectors, the configuration of the electricity grid is gaining importance. We research the grid planning of the future electricity grid with our own simulation models and a hardware-in-the-loop laboratory, which allows us to test new control systems for grid integration. The development of high-efficiency, durable and grid-supportive power electronics is a central focus of our research profile. We are working on medium-voltage power electronics, high-power converters and grid-forming inverters, which will make sustainable energy supply without fossil fuels feasible in future.

Facts and Figures

Total staff	156
Journal articles and contributions to books	17
Lectures and conference papers	31

Selected Projects in 2021

- HYBAT – Hybrid Lithium-Ion Battery Storage Solution with 1500 V Systems Technology, Innovative Thermal Management and Optimizing Operation Management
- Copernicus-Ariadne – Evidence-Based Assessment to Map Out the German Energy Transformation
- BKM_2.0 – Analysis of the Peer-to-Peer Marketing of Electricity and Development of an Accounting Grid Management System 2.0
- LamA-connect – BSI-Compliant Charging Using Smart Meter Gateways
- EnStadt:Pfaff – Decentralized Energy Management from the Smart Home to the Urban Quarter
- Q-Integral – Reactive Power Management in Use with Dynamic Reactive Power Sources at the Interface of Distribution Grid and Transmission Grid
- StraZNP – Strategic and Targeted Grid Planning

More information on these and further projects

More information on this business area

Fraunhofer ISE – a Reliable Partner

Contract Research for Our Clients

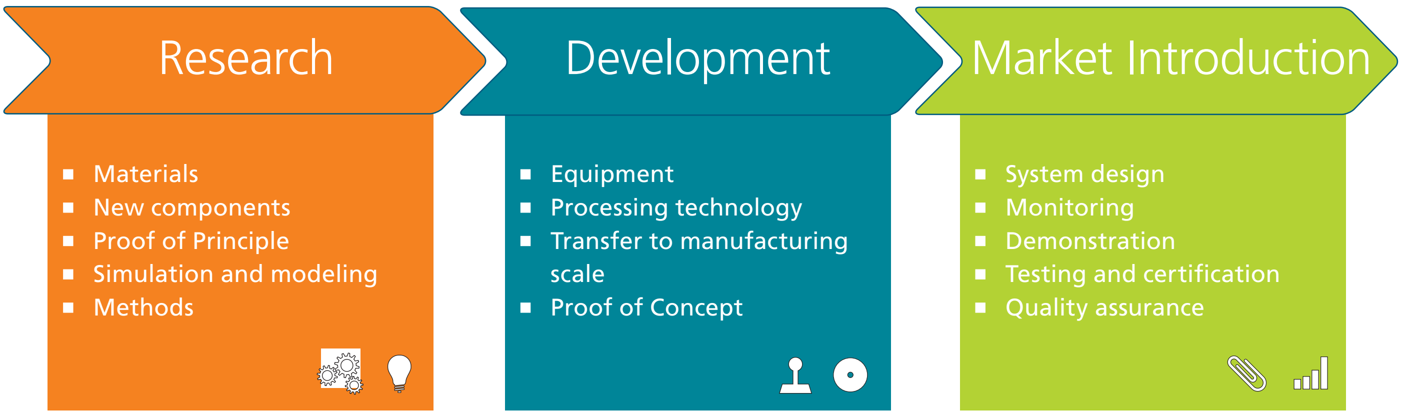
Contract research for clients from industry, science and politics is the primary activity of Fraunhofer ISE. We cooperate with project partners who are as diverse as they are numerous. At times, we are the substitute for an in-house research department in small and medium-sized enterprises. Large concerns profit from our specialized know-how and our excellent technical equipment. However, we also advise cities, local councils and educational institutions and carry out feasibility studies and modelling, to give two examples. Thus, we can develop customized solutions in accordance with our clients' requirements.

Contractually specified research and development projects with our partners from industry and research are at the core of our work. As the largest solar research institute in Europe, we are well connected in this sector, in politics and with associations, so that our clients also profit from cooperation with us via strategic partnerships and innovation clusters.

From the First Idea to a Marketable Product

Fraunhofer ISE accompanies its project partners with its broad spectrum of competence according to their requirements from the first idea to a marketable product. Together with our clients, we conduct research on new materials and components, develop new methods, carry out simulation and modeling, and prepare Proofs of Principle.

We develop prototypes and small series of new components and devices, transfer the production processes to manufacturing scale and conduct measurement-based analyses and Proofs of Concept. We also support our clients during the market introduction phase. We advise them during planning processes, prepare studies and examine possible system designs. In addition, we accompany research with testing and certification services in our accredited laboratories, which guarantee admission to the market for our clients' products. In the field, we offer monitoring and quality assurance for devices and systems.



Overview of Fraunhofer ISE's spectrum of services.

Expertise and Experience

After more than forty years of research and development, Fraunhofer ISE possesses profound knowledge of the market and extraordinary expertise. An important advantage of the Institute is its first-class technical infrastructure. Extremely modern laboratories and equipment for the entire spectrum of our business areas, which occupy a floor area of more than 20 900 m², are available to meet the needs of our clients.

Apart from scientific expertise, also targeted working approaches and reliable project management with well-established processes are essential for successful completion of R&D projects. Guaranteed confidentiality and professional agreements concerning utilization rights from patents and licences are a matter of course for us.

Surveys on Client Satisfaction

Quality assurance of our work is an important priority to ensure that we are always optimally orientated to the demands of the market. To this purpose, we conduct external audits of our work every year. In addition, we ask our clients regularly for their feedback. Our project partners regularly report great satisfaction, which is a source of pride and an incentive to us. We are also pleased about the large proportion of new contracts with returning clients and the long-term cooperation based on mutual trust with our clients that results.

"Our fortune and the fate of Fraunhofer ISE were very, very closely connected over forty years. I am looking forward also in the coming years to cooperation with Fraunhofer ISE based on mutual trust, to setting many world records together and, as an industrial enterprise, to continued benefit from the staff and infrastructure."

Jürgen Heizmann,
CEO AZUR SPACE Solar Power GmbH

"Fraunhofer ISE has supported us excellently in our fuel-cell development by high-quality long-term tests. We particularly appreciate the many years of experience and profound expertise of the scientists."«

Dr. Florian Henkel, responsible for Stack Assembly Module Component Development, cellcentric GmbH & Co. KG, a company in the Daimler Truck & Volvo group

"We are very pleased about the successful cooperation with Fraunhofer ISE, because our proposals were implemented quickly and enthusiastically. This was the basis for a successful project."

Volker Büge and Hellmuth Frey,
EnBW Energie Baden-Württemberg AG

"For the housing economy, climate-neutral and affordable housing is an important goal – and a major challenge. Support by Fraunhofer ISE is very welcome here."

Dr. Ingrid Vogler, Spokesperson for Energy, Technology and Standardization, GdW Bundesverband deutscher Wohnungs- und Immobilienunternehmen e.V.

R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of 20 900 m^2 – including 1 070 m^2 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 its seven accredited laboratories, Fraunhofer ISE offers diverse testing and certification procedures to commercial enterprises and scientific institutions. At present, the Institute has two calibration and five test laboratories with extremely modern technical equipment, which are accredited by the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body) (pages 46 ff.).

In our eight laboratory centers and four production-relevant technological evaluation centers, we develop new products, processes and services and optimize existing ones. In April 2021, we officially opened our most recent facility: the Center for High Efficiency Solar Cells (pages 50/51).

Technological Evaluation Centers

SiM-TEC – Silicon Materials Technology Evaluation Center

PV-TEC – Photovoltaic Technology Evaluation Center

Module-TEC – Module Technology Evaluation Center

Con-TEC – Concentrator Technology Evaluation Center

Laboratory Centers

Center for High Efficiency Solar Cells

Center for Optics and Surface Science

Center for Material Characterization and Durability Analysis

Center for Heating and Cooling Technologies

Center for Electrical Energy Storage

Center for Fuel Cells, Electrolysis and Synthetic Fuels

Center for Power Electronics and Sustainable Grids

Center for Emerging PV Technologies

In-line etching facility in PV-TEC Front End for ozone-based wafer purification and single-sided emitter removal.

Accredited Laboratories

CalLab
PV Cells

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

Wendy Schneider
Phone +49 761 4588-5146

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

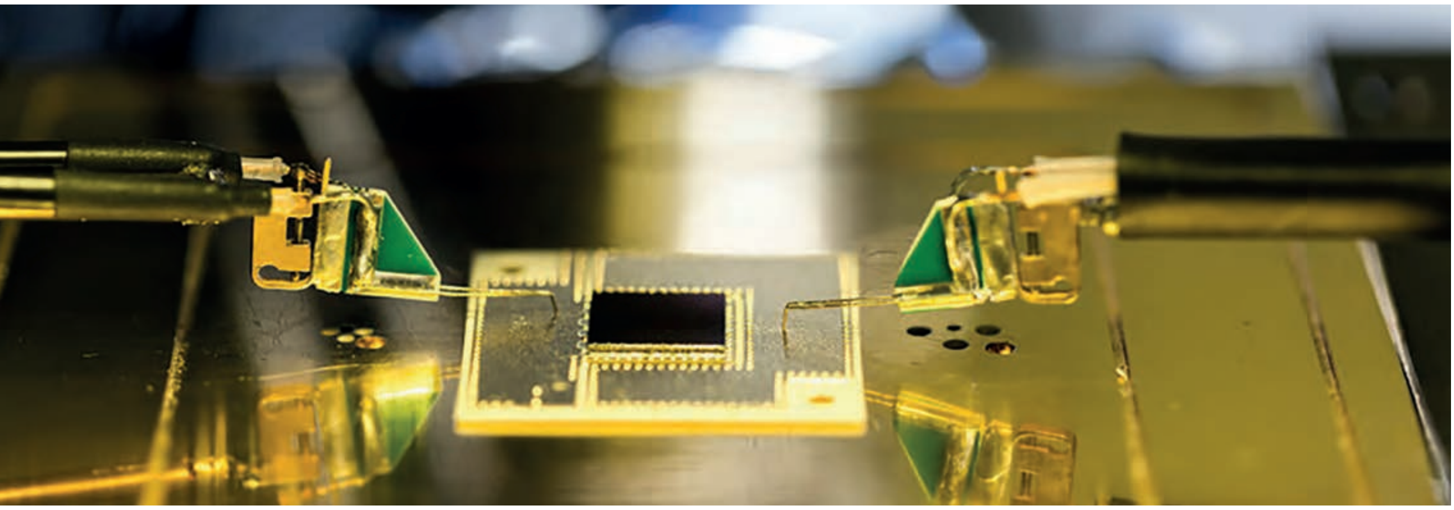
cells@callab.de

Calibration of Solar Cells

In CalLab PV Cells, we offer the calibration of solar cells representing a wide range of PV technology. It is accredited as a laboratory for solar cell calibration with the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body) and counts as one of the internationally leading photovoltaic calibration laboratories. In cooperation with PV manufacturers, and with the support of the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we work continuously on improving measurement tolerances and developing methods to measure new solar cell technologies accurately.

We can measure bifacial solar cells 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 yet greater accuracy and short measurement times. Furthermore, various multiple-source simulators allow us to make measurements of multi-junction solar cells under almost any standard conditions, such as are needed for space and concentrator applications.

In a new research field, we are addressing the measurement of photovoltaic cells for laser power conversion, 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.



Photovoltaic laser power conversion cell (10 x 10 mm²) to convert laser illumination into electric power.

Bifacial PV module in CalLab PV Modules.

CalLab
PV Modules

Calibration and Performance Tests of PV Modules

In CalLab PV Modules, we calibrate PV modules for production lines accurately, quickly and reliably. With an international record measurement uncertainty of only 1.1 %, confirmed by the Deutschen Akkreditierungsstelle DAkkS (German Accreditation Body), we calibrate reference objects 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 in the portfolio of almost all module manufacturers, as are bifacial technologies. Continuous development of new measurement methods and adapted measurement equipment 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 are entering the market. We offer accredited calibration also for these formats.

In addition, 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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Quality Assurance of PV Modules

TestLab PV Modules adresses the quality and reliability of PV modules. Our accredited laboratory is equipped with modern and innovative testing facilities for applications beyond standard testing procedures.

We advise our clients on cost-effective and time-efficient testing programmes as well as on individual quality criteria. In cooperation with our partner, the VDE Prüf- und Zertifizierungsinstitut, we offer product certification according to international standards.

The field of new cell and module concepts is very dynamic at present. Modules are becoming larger and more powerful, and the diversity of cell and connection concepts is increasing. Divided cells, shingle technology with and without connectors, multi-wire and tandem technologies play a major role here. The application areas are also constantly being developed further: Building or vehicle integration demand new 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 at an early phase and develop adapted methods. In doing so, we follow the goal of greatest accuracy and practical relevance. We contribute our experience and results within international standardization bodies.

TestLab
PV Modules

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Climatic chamber for different tests according to IEC 61215.

TestLab
Solar Façades

Test room at Fraunhofer ISE to evaluate the visual comfort of façade technologies.

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 and also "active" façade elements which 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 which often cannot be characterized adequately by conventional testing methods, such as building components with angle-dependent and polarization-dependent properties, light-scattering materials or structured and light-redirecting elements.

We have extensive research experience in solar-control systems, building-integrated photovoltaics (BIPV) and building-integrated solar thermal technology (BIST). BSDF data sets (bi-directional scattering distribution function) are determined goniometrically and are used in simulation programs to evaluate daylight use and glare.

In addition, TestLab Solar Façades is recognized as a notified body and is thus authorized to test building products with regard to energy economy. It is the European Regional Data Aggregator (RDA) for the National Fenestration Rating Council (NFRC) and advises European glazing manufacturers who intend to address the North American market with their products.

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TestLab
Solar Thermal Systems

Testing of Collectors, Storage Tanks and Systems

The portfolio of the accredited TestLab Solar Thermal Systems covers testing as the basis for market access and certification 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. Cooperation with the accredited TestLab PV Modules allows us also to offer measurements for complete certification of PVT collectors. To test hybrid heating systems, we work together with the accredited TestLab Heat Pumps and Chillers.

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 individually test the mechanical stability of mounting systems, PV modules and solar-thermal collectors 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. We carry out factory inspections for our clients around the world, also with remote procedures, within the Solar Keymark certification programme.

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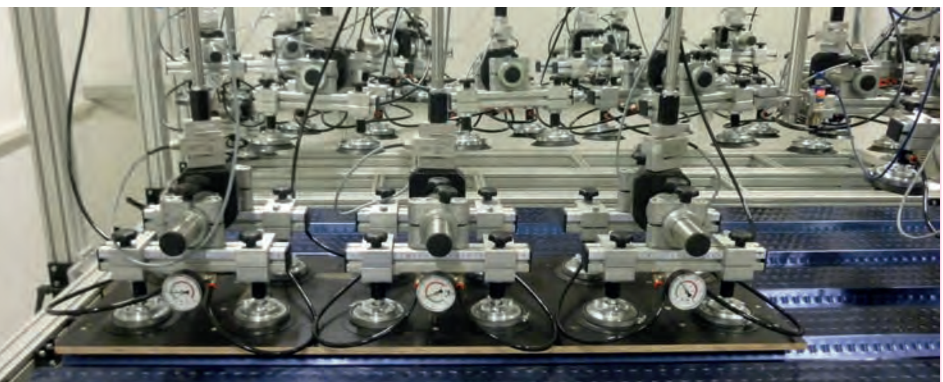
Testing a solar collector for mechanical resistance to underpressure and overpressure in the TestLab Solar Thermal Systems.



TestLab
Heat Pumps
and Chillers

Measurement and Testing of Heat Pumps and Chillers

In the TestLab Heat Pumps and Chillers, we develop, measure and characterize heat pumps and chillers, as well as their components. The modular test rig concept makes it feasible to test different types of technology and system configurations under operating conditions with different heat transfer media (air, water, brine). In addition to electrically driven systems, thermally driven equipment can also be measured. The laboratory is equipped with an integrated safety concept which allows components and systems with flammable refrigerants or ammonia to be measured.

Test objects with heating or cooling power of up to 100 kW 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 current (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, realistic measurement procedures.

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Measurement of the air temperature and humidity at the outlet of a heat pump installed outdoors.

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. 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 new laboratory enables us to test the electric properties of inverter systems, characterize them according to current grid connection guidelines and carry out climatic-chamber tests to clients' specifications. We mainly test PV and battery inverters, but also internal combustion engines for combined heat and power (CHP) plants or loads such as rapid charging stations for electromobility. The laboratory is equipped with different transformers, test rigs to simulate grid faults (up to 10 MVA), grid simulators (up to 1 MVA), DC sources (each 1 MW), protection testing devices and an RLC load for anti-islanding tests (400 kVA).

Furthermore, we offer our clients field measurements, for instance of large PV or wind power plants. For this purpose, we have six measurement systems, each with 16 measurement channels, which can be distributed and synchronized as required in the field.

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

TestLab
Power Electronics

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Medium-voltage switching equipment at the Center for Power Electronics and Sustainable Grids.

The New Center for High Efficiency Solar Cells

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"We are standing at the beginning of a solar revolution. And at the center of it is Fraunhofer ISE, one of the most important solar research centers of the world."

Winfried Kretschmann
Premier of the State of Baden-Württemberg on the occasion of the inauguration of the Center for High Efficiency Solar Cells in April 2021

Center for High Efficiency Solar Cells: View along the cleanroom corridor. The photolithographic area can be seen in the background.

Further information

On April 27th, 2021, our new Center for High Efficiency Solar Cells officially began operation. In the presence of the Premier of the State of Baden-Württemberg, Winfried Kretschmann, and other guests of honor, our laboratory building was officially opened. It was financed with funds from national German sources and the State of Baden-Württemberg.

We look back on a very successful event – with motivating greetings and speeches, which we were very pleased to hear. Unfortunately, due to the pandemic boundary conditions, only an online event was feasible. This did not affect the good atmosphere adversely but meant that we could not present the main actor of the day live, namely our new laboratory building – which would undoubtedly have been worth a visit: In the new Center for High Efficiency Solar Cells, we can test and optimize advanced PV technologies in extremely modern laboratories occupying an area of more than 1 080 m^2, 740 m^2 of it equipped as clean rooms. The research infrastructure lifts the heart of every single solar researcher:

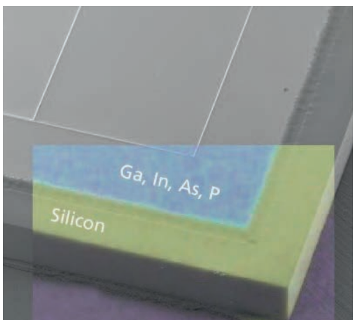
- high-temperature processes (BBr_3, $POCl_3$, O_2)
- ion implantation (P, B, H, Ga, Si)
- wet-chemical processes for purification and structuring
- yellow-light zone for photolithography and laser lithography to create microstructures with bifacial alignment
- wafer-bonding technology
- plasma technology (PECVD and LPCVD deposition and etching)
- atomic layer deposition (ALD) to deposit Al_2O_3, TiO_x, ITO, TCOs etc.
- processing of flexible wafer dimensions up to M4 (162×162 mm^2)
- thermal and electron beam evaporation of metals and dielectric layers
- electro-plating to create contacts on solar cells
- extensive characterization facilities for materials and components

The laboratory center offers us ideal opportunities to raise solar cells of silicon and III-V semiconductors to a new level. Fraunhofer ISE holds several world records for highest-efficiency solar cells, including for silicon solar cells contacted on both front and back (26.0 %). The world's best four-junction solar cells (46.1 % under concentrated light) were also produced at Fraunhofer ISE. Such top values can only be achieved under optimal conditions and with the best laboratory equipment. They represent the cutting edge of solar cell development and are simultaneously an inspiration for the industrial implementation of new solar cell types, which we are developing intensively in our photovoltaic pilot line, PV-TEC.

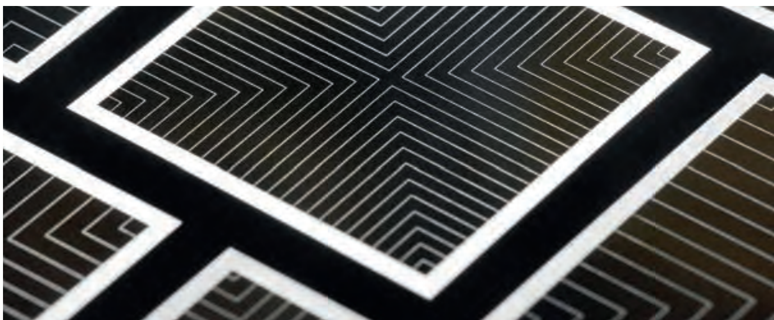
In parallel to further development of silicon and III-V technology, one focus of the new laboratory is on the combination of these two materials in the form of tandem solar cells (pages 24/25). Highest-efficiency silicon-based tandem cells are among the most promising photovoltaic technologies for the future and are included on the roadmaps of all relevant actors in the PV industry. We develop silicon-based tandem solar cells consisting of combinations of both silicon with III-V semiconductors and also silicon with perovskites. We do not restrict ourselves just to the tandem solar cell itself, but also apply our broadly based expertise to develop all stages of this new technology from the material up to the module.

The new Center for High Efficiency Solar Cells forms an important new building block for photovoltaic research at Fraunhofer ISE. It allows us, also in future, to develop path-breaking new types of solar cells, processes and technologies and thus to contribute to the competitiveness of the German PV industry.

Scanning electron microscope image of a III-V silicon tandem solar cell.



The TOPCoRE solar cell achieved a new world record of 26 % for a solar cell that is contacted on both surfaces.



Highlights of Our Research

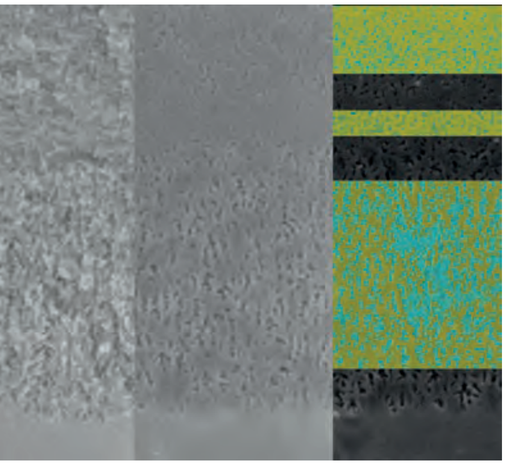
"

Our breadth of expertise enables us and our customers to help shape the energy transition in its entirety."

Prof. Hans-Martin Henning, Prof. Andreas Bett
Institute Directors, Fraunhofer ISE

Contents

Reusable Epitaxial Templates by Electrochemical Etching of Porous Layer Stacks



Cross-section of porous Si layer stack: simply broken (left), infiltrated and ground (middle) and with automatic visualization of porous areas (right).

The growth of monocrystalline wafers from the gas phase is becoming increasingly important in photovoltaics. In this process, so-called epitaxial wafers (EpiWafer) are deposited onto a separable epitaxial template that is located on a reusable substrate. The crystallographic and electronic quality of the EpiWafer is determined particularly by the quality of this epitaxial template. In order to keep costs low and the CO_2 footprint as small as possible, the substrate must be reused many times.

At Fraunhofer ISE, we have been working on reusable substrates of silicon and germanium for many years. Porous layers of differing thickness and porosity are etched in these sub--strates by applying electrochemical processes. If these substrates are subsequently heated in the epitaxy reactors in a hydrogen atmosphere, the surface heals completely to become an epitaxial template and a predetermined breaking plane forms at a deeper level which subsequently allows the epitaxially grown layer to be separated and the substrate to be reused. If in turn silicon is grown on a porous epitaxial template and this layer is separated, a Si EpiWafer results. Our NexWafe GmbH spin-off uses this approach and is developing it to commercial maturity. We support this with further-reaching developments in the laboratory.

Last year, we were able to significantly improve the quality and reliability of such epitaxial templates both on highly doped wafers of silicon and on germanium. The basis was provided by further developments in the characterization of the porous layers. The structure dimensions of a few nanometers and very brittle materials made it very challenging to generate high-resolution cross-sectional images using an electron microscope. By applying an infiltration process and an adapted cross-section polishing technique, we have now succeeded in creating cross-sectional images with a very good contrast ratio. In addition, the Dragonfly® software allows us to evaluate these high-contrast images automatically. Porosities and pore size distributions at the different layer depths are determined reliably, as illustrated here in the figure to the left, with porosities of 19 %, 16 % and 40 % (from top to bottom). In particular, this allowed our understanding of the inteaction between the ndividual electrochemical processes to be deepened significantly. With the system platform that was commissioned last year, we are able to etch porous layer structures without edge exclusion on wafer formats of up to 300 mm diameter (circular) or 166 mm x 166 mm edge length (square). The knowledge we have gained and the excellent equipment form an ideal basis for further improvements in quality.

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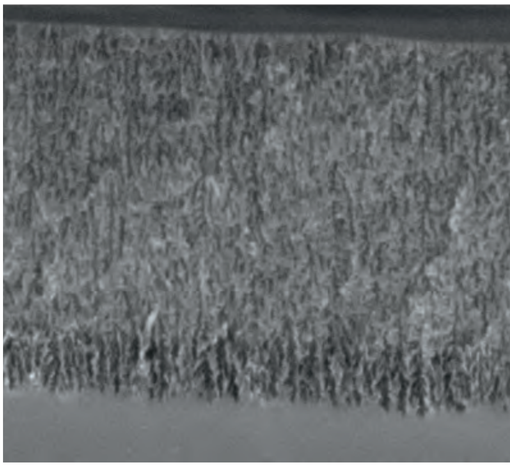
Electrochemical etching chamber with lighting and cooling unit for wafer sizes up to diameters of 300 mm.

Monitoring Porous Silicon Layers for Epitaxial Wafer Production with Inline Reflectance Spectroscopy

Manufacture of silicon wafers directly from the vapor phase by epitaxy with the so-called sintered porous silicon (SPS) method enables significant cost savings compared to conventional ingot growth and subsequent multiwire sawing, due to the absence of kerf loss. In this method, the surface of a substrate wafer is porosified and sintered to provide a growth platform for the epitaxial wafer (EpiWafer) and to enable its later separation. As a newly industrialized technology, kerf-free wafering requires that specific characterization needs be addressed. One of these requirements is reliable and non-destructive quality control of the porous layers.

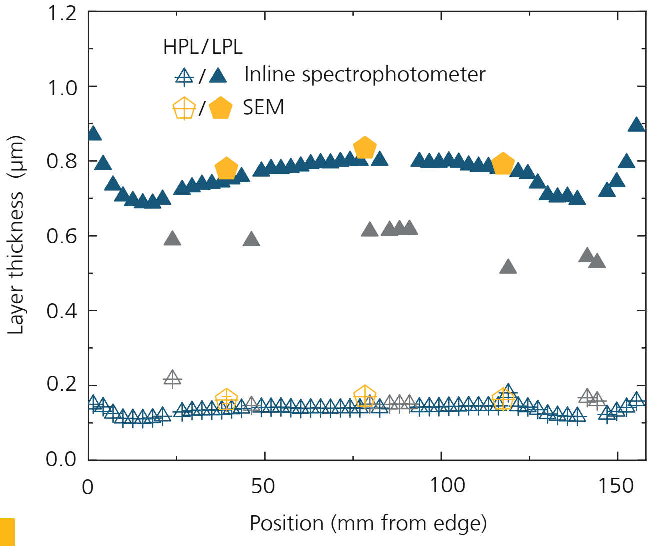


Scanning electron microscope (SEM) image of a porous silicon layer stack consisting of two layers with different porosities.

To enable the growth of the EpiWafer on the substrate and to facilitate its subsequent separation, etching of two separate porous silicon (PorSi) layers with different properties is necessary. In particular, the porous structure consists of a low-porosity layer (LPL), which after sintering and the associated reorganization of the porous structure provides a platform for the epitaxial growth. Further, a high-porosity layer (HPL) is formed below the LPL, which enables the separation of the EpiWafer from the substrate. The absolute values and the uniformity of the thicknesses and the porosities of both layers are essential to obtain a smooth growth platform at the epitaxial growth stage, and to achieve good detachability of the EpiWafer.

In the "Epi-Inspec" project, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we have addressed quality-control questions in collaboration with NexWafe, an epitaxial wafer manufacturer. We developed a non-destructive and rapid method for evaluating porous silicon stacks by using inline spectrophotometry. This analysis is based on model-based fitting of reflectance spectra, which enables the extraction of both the thicknesses and the porosities of the layers. Further, the technique enables the measurement of tens of points across the wafer while it is transported under the spectrophotometer on the conveyor belt. Hence, the method intrinsically allows the homogeneity of the layers to be evaluated along the entire wafer length.

The graph shows an example line scan of the thicknesses of the different porous silicon layers, obtained from the inline reflectance spectra with the model-based algorithm. The thicknesses based on this analysis are compared in the figure to values obtained from cross-sections with a scanning electron microscope (SEM). This comparison confirms that the reflectance analysis results in realistic layer thicknesses in the case of both the LPL and the HPL. In addition to the thicknesses of the layers, the fitting algorithm also provides line scans of porosity as output (data not shown). Due to the good agreement observed with the SEM images, the method is now routinely being used during wafer production at NexWafe.



Thicknesses of the low-porosity and high-porosity layers (LPL and HPL) as a function of the distance from the wafer edge. Gray points represent outliers.

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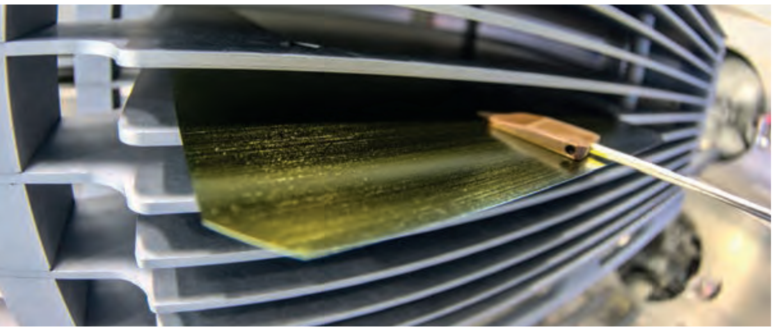
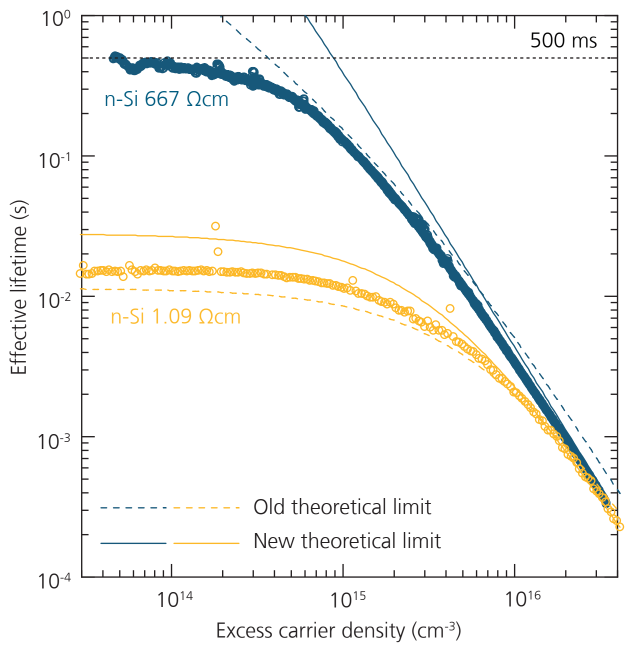
Auger Recombination in Silicon Redetermined Using TOPCon Passivated Samples



Preparation for TOPCon deposition in a PECVD facility.

Passivating contacts are a key technology for high-efficiency silicon solar cells. At Fraunhofer ISE, we are conducting intense research in this area and have produced solar cells with an efficiency of up to 26 % on the basis of the TOPCon (tunnel oxide passivating contact) technology that we developed. This corresponds to a record efficiency for solar cells that are contacted on both sides. During the past years, we have continually developed the TOPCon technology further and optimized it. In doing so, we succeeded in almost completely suppressing the charge carrier recombination in silicon samples with TOPCon surface passivation and have measured charge carrier lifetimes of up to 500 ms. This record value for charge carrier lifetimes in silicon wafers impressively demonstrates the exceptional surface passivation quality of the TOPCon technology and its suitability for future, high-efficiency silicon solar cells.

Apart from making high-efficiency solar cells feasible, this extremely efficient surface passivation also allows recombination processes in silicon wafers to be investigated with great accuracy. To determine the individual recombination mechanisms exactly, it is fundamentally important to characterize the intrinsic Auger recombination precisely. The accuracy with which this fundamental recombination process can be parametrized depends on how well other charge carrier recombination channels such as surface recombination can be suppressed. For Auger recombination, this is important because it has become evident in recent years that the previous parametrisation is no longer valid. In particular, the recombination in phosphorus-doped silicon with a specific resistance of about 1 Ω cm was significantly overestimated. This inaccuracy is very relevant, not only for various characterization methods, but also for the simulation and optimization of solar cells, as the significance of Auger recombination as a loss channel increases with increasing cell efficiency. Against this background, we have newly determined the parameters for Auger recombination in crystalline silicon in international cooperation with the Australian National University, the University of Warwick, the Institute for Solar Energy Research in Hamelin (ISFH) and the University of Freiburg. Within this fruitful cooperation, in recent years we have investigated and compared the types of sample preparation and characterization to eliminate systematic errors as far as possible. On this basis, a reliable, universally valid parametrization of this fundamental material quantity has been achieved, which is of importance not only for silicon photovoltaics but also for many other silicon-based semiconductor devices.

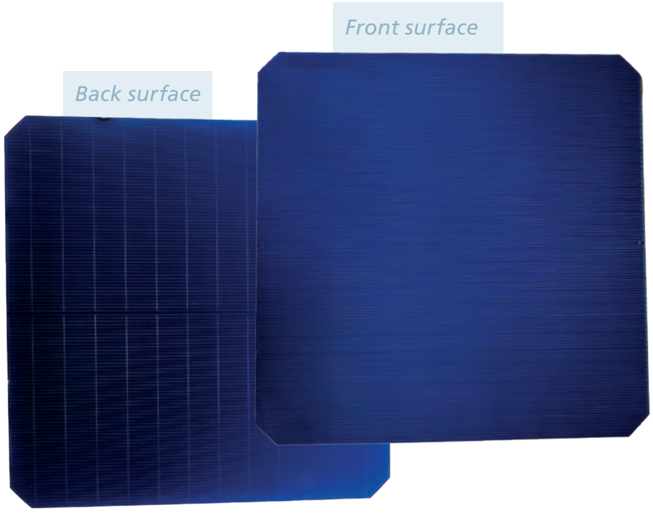


Measured lifetime curves together with the old and the newly determined intrinsic upper limit.

Process Technology for Cost-Effective Mass Production of TOPCon Solar Cells

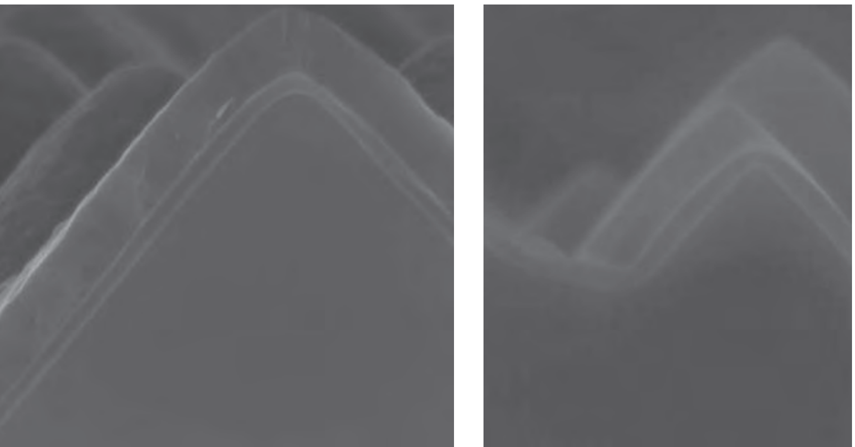
At present, silicon solar cells with passivating contacts are being introduced increasingly into industrial production. The TOPCon (tunnel oxide passivated contact) technology, which was developed at Fraunhofer ISE, has now been transferred to our large-scale prototype laboratory, PV-TEC. There, we have established a basic processing sequence to produce such solar cells, in which predominantly large industrial machines are used. Due to the high throughput, we are able to conduct experiments involving several hundred wafers. These industrial solar cells of n-type silicon feature the name-giving, phosphorus-doped TOPCon layer stack on the back surface and a boron-doped emitter on the front. At present, we achieve efficiencies of up to 23.8 % on full-size TOPCon cells (cell area: 244 cm²) with open circuit voltages exceeding 700 mV. The processing sequence is the basis for cooperation with various industrial partners of Fraunhofer ISE and the object of continuous further developments.

A major challenge to the industrial production of TOPCon solar cells is the removal of unwanted wrap-around of the polycrystalline Si layer from its back-surface deposition onto the front of the cell. An industrially applicable procedure was developed to do this in PV-TEC, which is based on atmospheric pressure dry etching (ADE) applying F_2. In comparison to previously applied wet-chemical procedures, ADE reduces the processing costs and makes higher throughput feasible due to a very high etching rate of more than 3 µm/min. In addition, the process is confined well to one surface, such that the polycrystalline Si layer on the back of the solar cell is retained completely. Simultaneous removal of the polycrystalline layer along the edge of the wafer leads to high stability of the solar cells under application of negative voltages – an important prerequisite for the integration of the solar cells into PV modules.



Front and back surfaces of a bifacial TOPCon solar cell produced in PV-TEC at Fraunhofer ISE.

The currently applied screen printing metallization procedures require polycrystalline Si layer thicknesses of about 150 nm to 200 nm to prevent the metallization from being fired through the layer stack. This causes high costs for the layer deposition and the thick layer has a negative effect on the short circuit current density of the solar cell. As a result of successful cooperation with an industrial partner, Fraunhofer ISE can now apply the novel laser-enhanced contact optimization (LECO) process to create contacts. This has now been applied successfully to very thin polycrystalline Si layers for the first time. The solar cells with conventional screen printed metallization that were contacted this way achieve the same efficiency of 23.3 %, with a layer thickness of 80 nm, as the reference process with 170 nm layer thickness (cell area in each case: 244 cm²).



Scanning electron microscope image of a cross-section of the solar cell front surface, before removal of the TOPCon layer by ADE (left) and afterwards (right).

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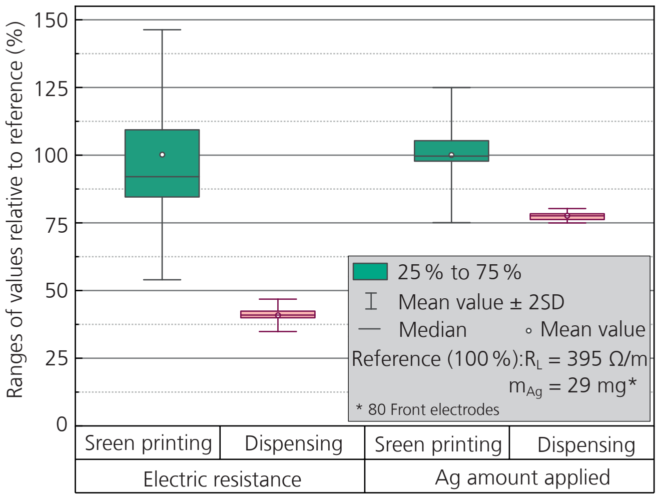
High-Throughput Dispensing Technology to Reduce Silver Consumption for Solar Cell Metallization

The industry and applied research are working constantly on improving the usage of resources and raising production throughput for the metallization of solar cells. With this goal, Fraunhofer ISE has developed the so-called parallel dispensing procedure as an alternative metallization process. In this printing process, highly filled metal paste is extruded through up to 200 parallel micro-nozzles and applied without contact to the silicon wafer. To date, we have demonstrated processing rates of up to 1000 mm/s for PERC metallization and up to 600 mm/s for the heterojunction application.

In the latter case, primarily so-called low-temperature pastes are applied, which feature a relatively high polymer content. This gives the metal paste a certain stretchability, which means that the paste filament between the nozzle outlet and the substrate can be stretched such that the cross-sectional area becomes smaller (figure below).

A further advantage of the dispensing technology becomes evident if the conventionally used screen printing process is examined more closely. The screen mesh typically causes indentations in the structure, which locally reduce the height of the contact and thus increase the electrical resistance. This problem does not exist in the dispensing procedure, meaning that dispensed contacts feature a very homogeneous cross-sectional area. The combination of both effects leads to significant improvement in the relationship between the amount of material (silver) used and the resistance of the contact (figure above).

We are developing the dispensing technology in several publicly funded joint projects. For example, metal grids are applied to thin-film solar cell modules (CIGS) within the "altura" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). We have succesfully demonstrated performance advantages in the metallization of CIGS modules. In addition, the dispensed metal grids allow wider cells to be used in the CIGS module than is possible with the classic screen printing process, such that the active area in the module can be maximized. In a next step, suitable metal pastes for drying temperatures below 200 °C are to be evaluated. The goal was to prevent voltage losses due to damage to the temperature-sensitive layers of thin-film solar cells. Further development work is occurring in the "PrEsto" and "BUSSARD" joint projects, which are also funded by the BMWK, and where we are researching the metallization of perovskite-tandem solar cells and TOPCon solar cells, respectively.



Advantages of dispensing technology.

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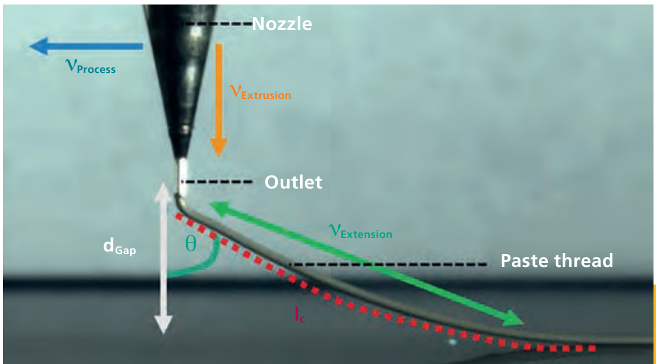


Influence of rheological properties on filament stretching during dispensing.

Moving Toward the Mass Market: Copper Electroplating for Silicon Solar Cells

Research has been conducted at Fraunhofer ISE for more than a decade on the metallization of silicon solar cells with copper contacts. As copper is about 100 times cheaper than the current standard material, silver, possible cost reductions were the main motivation in the past to develop the electroplating procedure to deposit copper onto solar cells.

However, current changes in the global photovoltaic market have created new stimuli: Recent prognoses predict strong growth up to the terawatt scale. Unless the silver consumption is reduced appreciably or even replaced completely, the growth rates in PV production would lead to the situation already in 2030 that the complete global annual production of silver would have to be used for manufacturing silicon solar cells.

Copper, with almost the same conductivity and lower material costs, offers further advantages compared to silver: Its CO_2 footprint is about 50 times smaller and the amount mined annually is about 650 times larger.

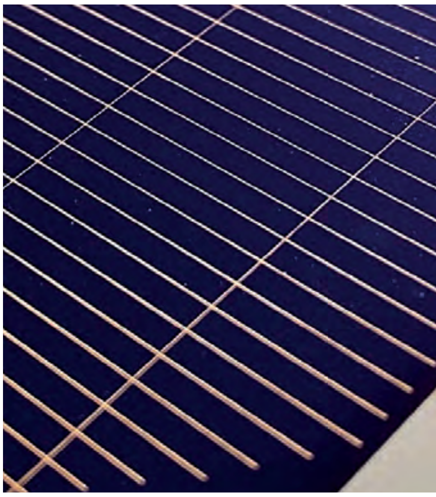
Fraunhofer ISE is cooperating with its industrial partners in several projects to develop copper electroplating for next-generation solar cells with passivating contacts and metal fingers on the front and back surfaces.

Within the »TALER« and »TopCon Cluster« projects, which are funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we have achieved efficiencies of up to 23.8 % for solar cells with passivating TOPCon contacts in industrial formats. In addition to saving more than 90 % silver, we even succeeded in increasing the efficiency compared to conventionally metallized references by 0.4 %. The improvement results from the higher short circuit current due to reduced shading by the extremely narrow contacts (see figure below). In addition, the fill factor of the solar cells is higher than for the reference, which underlines the electrical quality of the metallization.

Further work is being prepared for TOPCon electroplating to transfer the developed procedures from the laboratory to industrial-scale systems.

Furthermore, we at Fraunhofer ISE have developed and patented an electroplating process for heterojunction solar cells (HJT), which is based on multi-functional PVD layers instead of complicated masking techniques. Such layers are required anyway in the manufacturing process for HJT solar cells, so the process can be integrated seamlessly into the processing sequence. With this so-called "NOBLE" process (native oxide barrier layer for selective electroplating), currently efficiencies are achieved that almost equal those of the reference, for savings in silver of more than 95 %.

The path to transfer this process into the mass market is being smoothed by the Fraunhofer ISE spin-off, "PV2Plus". It will deliver the technology to interested manufacturers of silicon heterojunction solar cells and optimize it together with production equipment manufacturers for industrial application.



Photograph and microscope image of copper contacts on a silicon heterojunction solar cell produced with the "NOBLE" process.

Electron microscope image of the cross-section of an electroplated copper contact on a TOPCon solar cell.

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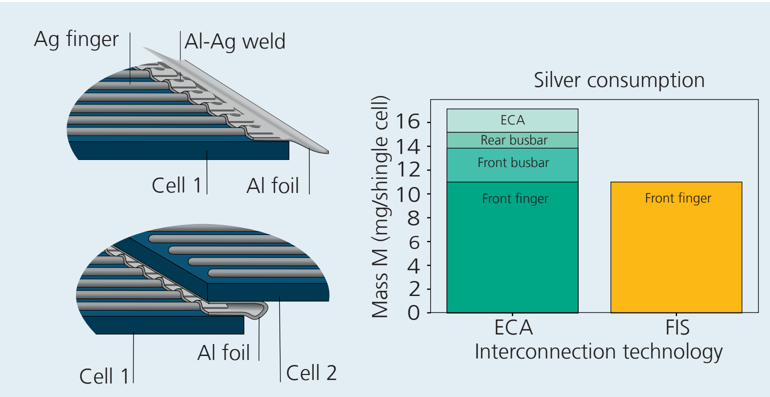
30 % Savings in Silver by Shingle Cell Connection with Laser-Welded Aluminum Foil



Representation of the FoilMet®-Interconnect shingling (FIS) cell connection (left); silver consumption of a shingle solar cell for two different connection technologies, ECA (electrically conductive adhesive) and FIS (right).

In the manufacturing of silicon wafers and cells, the trend is toward larger formats which range up to an edge length of about 210 mm. However, large cells lead to higher currents, which causes the contribution of series resistance in modules to increase. One option to decrease the module losses is to reduce the current by connecting separated cells such as half-cells and shingle cells. In modules with shingled solar cells, neighboring solar cells overlap along their edges. In this way, much of the metallization can be achieved in the space between cells, so outside the active cell area. The typical approach to connect solar cells applies electrically conductive adhesive (ECA), which connects the back busbar of one cell with the front busbar of a neighboring cell. ECAs are polymer-based adhesives which contain electrically conductive particles, usually of silver. Due to the low price of aluminum in comparison to silver, there is great interest in the solar industry in using aluminum foil for the connection.

With our innovative FoilMet-Interconnect Shingling (FIS), we leave out the high-silver screen printing steps for the busbars of the shingle solar cell and the application of ECA, and use an 8 µm thick aluminum foil instead (figure below). The aluminum foil is welded directly to the silver and aluminum fingers, so there is no need for busbar-type structures or ECA. In this way, the innovative FIS technology saves about 30 % silver in a module (figure on the left).

As the FIS technology allows cells without busbars to be used, it also simplifies the metallization layout for cells and offers the module manufacturers more freedom in their choice of cells. Furthermore, FIS results in very low electric series resistances. In two experiments with strings consisting of three and six cells, a fill factor exceeding 80 % was achieved and no degradation of the cell connection was observed in subsequent aging tests. Both experiments demonstrated that FIS can be a route to achieve low-resistance and highly efficient connection. As the aluminum foil is welded directly onto the electrodes of neighboring cells, potentially FIS can be applied for almost all metallization and cell concepts.

The technology, which has been filed for a patent, uses the potential of laser-welded aluminum foil. It represents a cost-effective and flexible solution for the connection of shingle solar cells. It also offers significant opportunities to conserve resources and leads to potentially higher module efficiency due to the low series-resistance contribution of aluminum foil.

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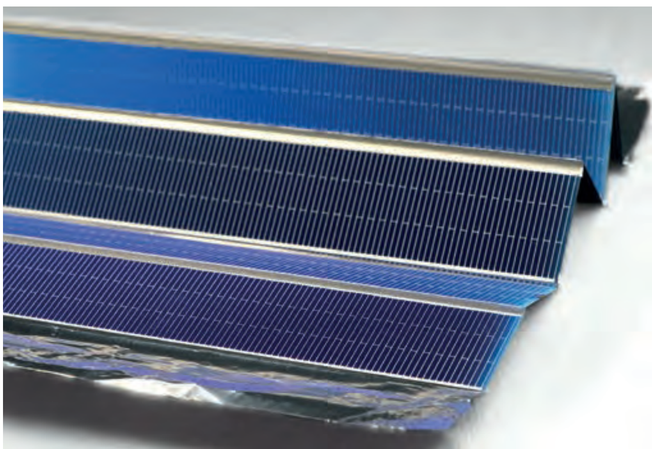
Six shingle cells connected with FIS. The concertina configuration demonstrates the flexibility of the cell connections.



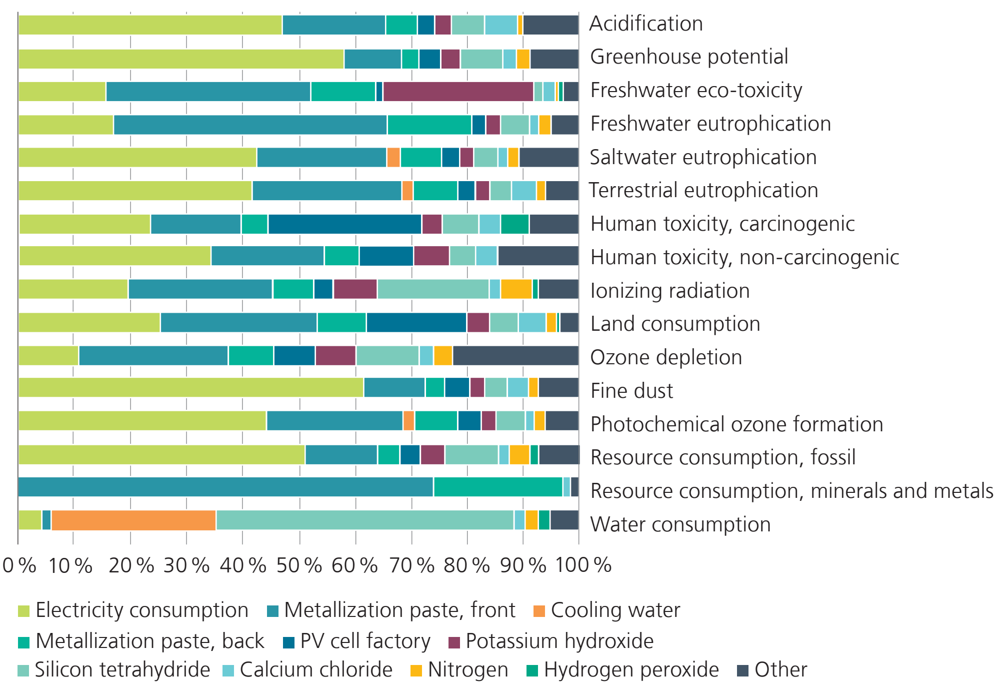
Green Manufacturing – Ecological Balancing for a Resource-Efficient PV Value Chain

According to prognoses, growth is anticipated in the PV market from currently about 740 GW installed capacity worldwide to about 2840 GW in 2030. It is thus urgently necessary to redesign current production systems to become more resource-efficient. Outputs of waste materials and wastewater must be minimized and converted into supplies of usable materials. In addition, improving the resource efficiency of the PV manufacturing chain also offers the opportunity to reduce manufacturing costs and thus to promote the marketing of the final product. Essential prerequisites to achieve this are the corresponding purification and recycling processes which must be implemented when PV production lines are constructed and taken into operation.

Within the "Green Manufacturing" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is researching the improvement of the circular economy at the factory level. In doing so, we apply concepts from life cycle analysis (LCA) and economic evaluation as well as analyses of the ecological efficiency and hazardous materials. We are working on both an example of integrated c-Si ingot / wafer, solar cell and PV module production and also thin-film PV module production. We analyse the complete value chain from procuring raw materials to the final module production and take into account not only industrially established processes and products but also PV technology, which is still under development, e.g. perovskite solar cells.

As an example, the graph shows the results of a hot spot analysis for a typical PERC cell production process located in China. In eight of 16 impact categories, the electricity consumption proves to be a decisive parameter for negative environmental effects. Its relative effect is particularly high in the categories of fine dust, greenhouse potential and resource consumption, which can be explained by the large proportion of electricity from coal-fired power stations in the Chinese electricity mixture. More than 50 % in total of the electricity there is generated using coal. Also, in six of 16 categories, the metallization paste is identified as the cause of greatest environmental impact. More than 70 % of the impacts in the "resource consumption, minerals and metals" category and about 50 % of the negative effects in the "eutrophication of freshwater" category are attributed to the metallization paste. The metallization paste also plays the largest role in the categories of freshwater eco-toxicity and land consumption, which is due to the high silver content of the paste and the associated mining and processing steps of metal extraction.

The project results already allow us to gain detailed information on the potential advantages of vertically integrated production sites and suitable optimization measures to reduce, treat and recycle waste and to develop approaches to deliberately replace specific materials used in production.



Hotspot analysis according to impact categories related to 1 m² of solar cells produced in China. Normalization methodology according to the "Environmental Footprint 3.0" methodology.

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Simulation-Supported Analysis and Optimization of Perovskite-Silicon Tandem Solar Cells

Perovskite-silicon tandem solar cells achieve higher effiencies than solar cells made only of silicon. In order to fully exploit this advantage and thus reduce the levelized cost of electricity, the manufacturing of both the upper perovskite solar cell (top cell) and the lower silicon solar cell (bottom cell) must be cost-effective.

View into the processing laboratory for wet-chemical perovskite deposition at Fraunhofer ISE.

Silicon bottom cells in a research context are often produced on the basis of silicon heterojunction technology (SHJ). By contrast, primarily the passivated emitter and rear contact (PERC) or in future also passivating polycrystalline Si/SiO_2 contact (TOPCon) technologies are applied for industrial silicon solar cell production. At Fraunhofer ISE, we have thus investigated the efficiency and production costs of perovskite-silicon tandem solar cells with different bottom cells by simulation-supported analysis. On this basis, we then calculated the levelized cost of electricity (LCOE). One result of the analysis is that significantly lower LCOE than for silicon solar cells can be expected for perovskite-silicon tandem solar cells with all bottom cell concepts. The highest efficiency was determined for tandem solar cells with SHJ bottom cells. However, the production costs for this case are also highest. As a result, the LCOE is similar for all types of bottom cells. Thus, solar cell producers can achieve the transition to tandem solar cells with different bottom cell technologies, building on their previous experience and preferences. Correspondingly, Fraunhofer ISE has prepared perovskite-silicon tandem solar cells on the basis of SHJ, TOPCon structures and tunnel oxide passivated emitter and rear contact (TOPerc) structures.

Another field of work is the optimization of the front electrodes of perovskite-silicon tandem solar cells. Two main requirements must be met: deposition of a highly transparent conductive oxide in a process that is as cost-effective and gentle as possible on the one hand, and metallization with low contact and conductive resistances at low temperatures, combined with compatibility with module constructions on the other. In a comprehensive simulation study, we determined the optimal parameters for the various technologies. Now we are cooperating with project partners to implement them. Dispensing technology holds promise for particularly fine contact lines and low silver consumption. We also demonstrated the deposition of silver-free copper contacts by electroplating onto a perovskite solar cell for the first time in the world. This work opens new perspectives for resource-conserving, low-silver or no-silver metallization concepts also for perovskite-silicon tandem solar cells. Within the Fraunhofer "MaNiTU" flagship project, we are now in the process of applying the promising tandem technology on large areas with industrially relevant processes.

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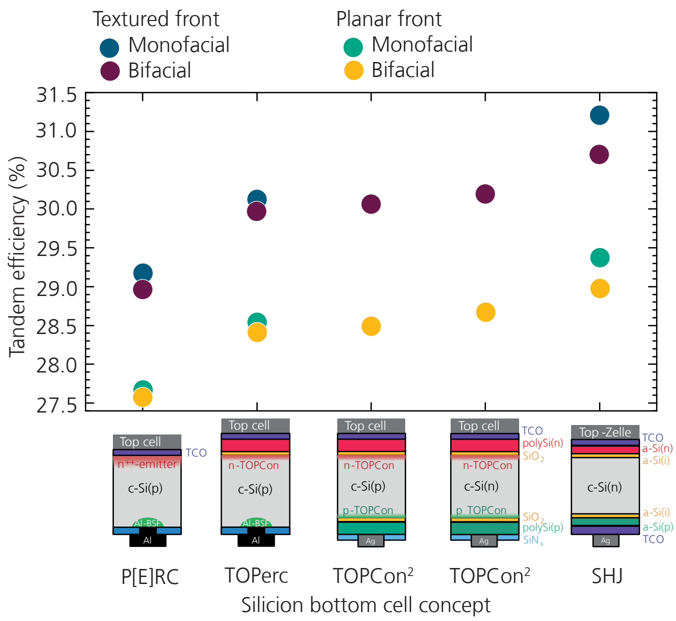
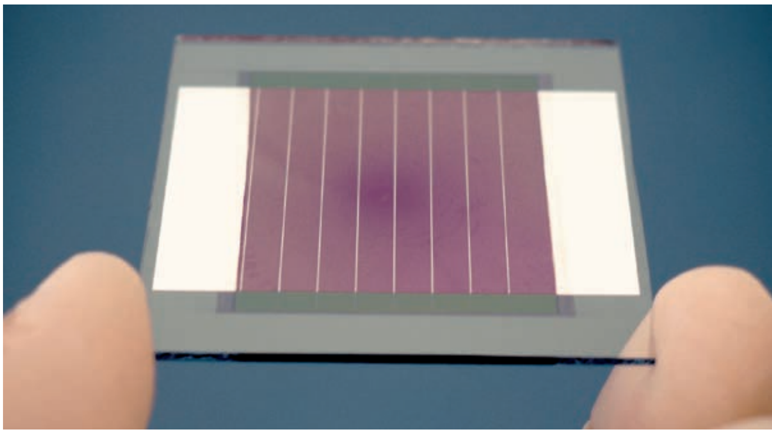


Efficiency potentials for perovskite-silicon tandem cells for different bottom cell structures.

Organic Photovoltaics: New Record Efficiencies for Cells and Mini-Modules

Only small quantities of energy are needed to manufacture organic photovoltaic modules. In addition, organic photovoltaics (OVP) features a high degree of design freedom and integration potential, low weight, attractive colors and mechanical flexibility. These specific advantages facilitate access to completely new installation surface areas that solar cells of crystalline silicon can address only to a very limited extent or not at all.



Mini-module with an area of 9 cm² made of organic solar cells that achieves a certified efficiency of 13.94 %.

Nevertheless, with values from about 10 % to 12 % for small-scale laboratory cells, the efficiency of organic solar cells was too low until recently to address new application fields, as losses occur during upscaling to large-area modules. During the past few years, however, a very dynamic development with regard to material synthesis has been observed: Particularly the properties of organic semiconductors that are used in the absorber layer were improved appreciably, and as organic synthetic chemistry offers manifold possibilities here, further improvements can be expected in the near future. Based on the optimized materials, the efficiency for organic solar cells increased significantly in recent years. However, this mostly applies to solar cells with very small areas of considerably less than 0.1 cm².

At Fraunhofer ISE, we have achieved a certified record efficiency of 15.24 % for a cell area exceeding 1 cm² – an important intermediate step toward large-scale modules – within the "H2OPV" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). A detailed analysis revealed that this value can still be increased appreciably on the basis of the organic absorber material used. Building on these promising results, we have prepared the design for a so-called mini-module, in which the structuring of all layers is done using a laser. We succeeded in achieving a certified record efficiency of 13.94 % for an area of 9 cm². The high value indicates that the very good coating quality can now also be implemented over the larger area. At present, we are working on transfering the results to significantly larger areas by slot-die coating. In doing so, we use the so-called inverted cell stack that we developed, which avoids the use of an indium tin oxide electrode layer. The advantage is that the processes can be directly transferred to the production of flexible organic solar modules by roll-to-roll coating.

In addition to this work, which forms the foundation for accessing new markets in future, a further application field should be named, for which organic photovoltaics has just reached commercial maturity: providing electricity indoors to electronic components in the "Internet of Things" (IoT) sector. There, organic solar cells today are already more efficient than solar cells of crystalline or amorphous silicon, and their durability under these "mild" conditions is sufficiently good. Fraunhofer ISE is developing flexible modules that do not contain indium tin oxide for this application and has already achieved efficiencies exceeding 15 %.

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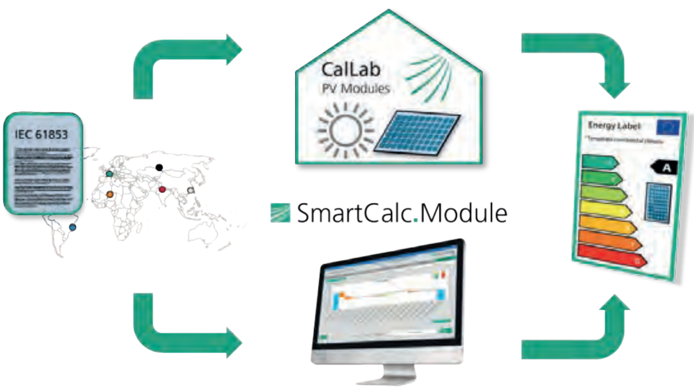
Better Comparability Between Modules with Virtual Energy Rating

The real value of a solar module is demonstrated by its electricity yield over its service life. Before commissioning, however, it is not easy to compare modules, as this yield depends on many factors, not only on the module properties. Laboratory characteristics such as the rated power under standard test conditions (STC) can easily be compared to each other, but only present part of the whole picture. A comparison of potential electricity yields can thus lead to significantly different results.

With the "Climate-Specific Energy Rating" (IEC 61853), we have implemented a procedure at Fraunhofer ISE which makes it feasible to compare modules on the basis of their performance in operation. Based on measurements under different conditions, the module behavior is characterized for selected operating points (irradiance, temperature). In a second step, we apply an interpolation algorithm which determines the module power for conditions that were not measured directly.

Comparable module evaluation applying Energy Rating based on simulation and measurement.



Finally, a module yield calculation is made on the basis of the interpolated measured values for standardized reference locations – which each correspond to a particular climatic zone – and converted to an effective energy rating.

The advantages of the procedure are that it is simple and rapid to apply and it provides reliable information that allows modules to be compared. It is therefore planned to integrate the energy rating according to IEC 61853 into the eco-design ordinance and the European energy label for solar modules, which should be introduced from 2023. The measurements needed for the energy rating can be carried out in the CalLab PV Modules at Fraunhofer ISE with high precision.

As an alternative to measurement, we can also simulate the module behavior with the "SmartCalc.Module" software developed by Fraunhofer ISE. An analogous energy rating to the IEC 61853 is also possible based on the simulation results for the digital module twin. The module behavior under any given operating conditions can be digitally modeled by applying coupled multi-physics simulation. Material parameters and characteristics for the component solar cells are needed for the virtual model of the module, but not measurements on the module as such. Thus, the potential yield can be determined and the module design can be optimized already during early phases of development. The procedure is particularly flexible, rapid and cost-effective in comparison to the measurement-based procedure. Module components and designs can be optimized, development road maps evaluated and technologies compared.

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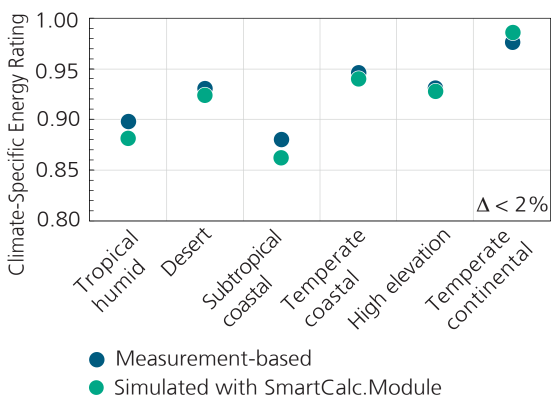
Workflow for the Climate-Specific Energy Rating of a module for different locations, applying measurement-based and a simultion-based approaches according to IEC 61853.



Efficient Lightweight PV Modules for Utility Vehicles

In recent years, strongly reduced costs and increased efficiency have made photovoltaic modules increasingly attractive for integration into vehicles. Particularly the large roof areas of utility vehicles are well suited for application-optimized PV modules with a lightweight construction.

Increasing numbers of manufacturers are offering electric trucks with traction batteries that can be partially charged with solar electricity generated directly on the vehicle. Integrated photovoltaics can also partially supply cooling units with electricity on diesel-fuelled trucks.

A new study by Fraunhofer ISE demonstrates that in Europe, 5 % to 9 % of the annual energy demand for an electric semi-trailer can be met by vehicle-integrated PV (VIPV). For other vehicle categories, for example transporters, calculations indicate that even more than a third of the energy demand can be met by VIPV. This was confirmed by a measurement campaign by Fraunhofer ISE from 2017. It demonstrated that PV modules integrated onto a typical 40-ton semi-trailer can generate between 5 300 and 7 400 kWh annually. This corresponds to savings of app. 5 % to 7 % of the annual energy demand.

In the "Lade-PV" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is cooperating with TBV Kühlfahrzeuge GmbH, Sunset Energietechnik GmbH, Alexander Bürkle GmbH & Co. KG and M&P Motion Control and Power Electronics GmbH as project partners on solutions for integrating PV modules into utility vehicles. As part of the project, an 18-ton electric truck has now been taken into operation as a demonstration vehicle. The PV modules were coupled in such a way that they could be fed directly into the high-voltage battery, taking all safety requirements into account.

Electric trucks and other utility vehicles, including non-electric ones, can save energy with solar power.

The power electronic integration of the PV modules and thus the connection to the vehicle battery is particularly critical due to the high voltage of > 300 V on the PV side. A specific development within the project, which has been registered for a patent made it possible to meet the safety requirements for road transport and for PV systems and connect the modules directly to the high-voltage system in the vehicle.

The integrated PV modules increase the mass of the vehicle by less than 4.5 kg/m² compared to a refrigerated vehicle with a conventional sandwich roof. In the demonstration truck, this corresponds to an additional mass of only app. 80 kg for the PV modules. The PV modules are integrated completely into the outer skin of the truck body. They do not have any protruding parts and increase the height by a maximum of 5 mm.

The robustness of the modules under extreme thermal and mechanical loads has been demonstrated in aging and load tests within the project.

The DC/DC converter and the service disconnect box are mounted under the truck body, saving space in the vehicle.

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Area Potential for Floating Solar Power Plants in Baden-Württemberg

Floating PV (FPV) as a form of integrated photovoltaics opens up new potential areas and helps to avoid land usage conflicts. Already about 3 GW_p has been installed around the world but in Germany there have been only a few small projects up to now. Fraunhofer ISE has calculated that the technical FPV potential on artificial water areas alone is 44 GW_p in Germany.

Against this background, we have determined the theoretical, technical and economically feasible potential that could be exploited for FPV technology in the State of Baden-Württemberg within a project that is funded by the State Ministry for the Environment, Climate and Energy Economy. The goal was to use geographic information systems (GIS) to determine this at the level of individual bodies of water and taking local boundary conditions into account. To conduct the potential analysis, we initially defined a catalogue of hard and soft restriction criteria for FPV installations. Hard restriction criteria represent clear criteria for elimination, whereas soft restriction criteria only result in classification in a lower suitability class. The individual criteria are intended both to take account of technical aspects and to prevent ecological or hydrological destabilization of the water body. In agreement with the client's specification, the potential analysis was restricted to dredging lakes in active operation.

Three scenarios with different area coverage ratios and lake area utilization efficiencies were prepared for the potential calculation. To different degrees, these scenarios take into account that covering too much of the water area can affect its ecological and hydrological equilibrium. The first scenario reflects a low lake-area utilization efficiency of 0.6 MW_p/ha and no upper limit in the area coverage, whereas the second and third scenarios feature higher lake-area utilization efficiencies of 1.18 MW_p/ha for maximal area coverages of 10 % and 45 %, respectively.

Based on the analysis, more than 60 suitable and conditionally suitable active dredging lakes with a total area of app. 1 700 ha were identified. The greatest FPV potential is located in the southern und central Upper Rhine regions, particularly in the districts of Karlsruhe, Rastatt and the Ortenau.

Finally, three FPV systems with the same installed rated power but different types of mounting were simulated at one location chosen as an example. These mounting structures take different local conditions into account but show similar specific yields of about 1 100 kWh per kW_p and year.

The study demonstrates that it is possible to analyse the FPV potentials of large regions at the individual water-body level rapidly by applying GIS methods. The uncertainty which occurs with regard to ecological and administrative boundary conditions can be taken into account with different scenarios. This approach demonstrated that, even with a focus on a small subset of existing artificial bodies of water, there is potential for FPV electricity generation in Baden-Württemberg which amounts to a tenth to a seventh of the total annual electricity consumption in that state.

FPV power plant in Renchen/Baden, where hydrological and ecological studies are carried out.

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Non-Destructive Investigation of PV Modules

Non-destructive investigation methods play an important role in evaluating the reliability of PV modules, as they allow aging effects and mechanisms to be detected and assessed without damaging the test object. This makes it feasible, for example, to observe the progress of aging phenomena in several steps during outdoor exposure or between aging tests, and to react flexibly to initial test results.

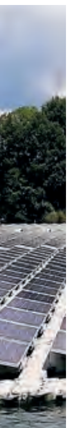
Scanning acoustic microscope during measurement of a 4-cell module.

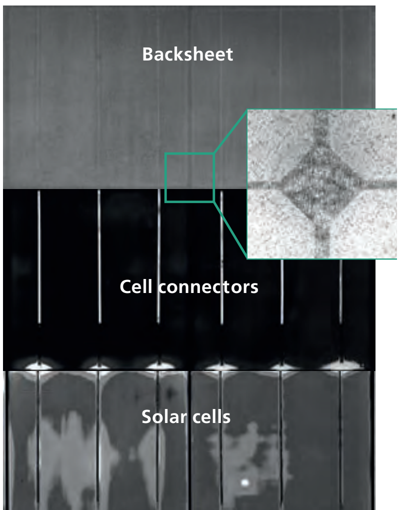
In addition to conventional, non-destructive methods such as Raman spectroscopy or dark lock-in thermography, the functional principle of scanning acoustic microscopy (SAM) is based on excitation with ultrasonic waves that are reflected by material interfaces. By subsequent processing of the reflected signal, information can be obtained on mechanical properties, material thickness or defects in different material layers of the PV module laminate. Depending on the excitation frequency and measurement parameters, specific components of PV modules, such as the different layers of the backsheet, encapsulation polymers, connectors, solar cells and glass panes, can be investigated to address the question of interest.

By recording many neighboring measurement positions in a 2D grid, it is also possible to generate images of specific material layers. Depending on the choice of excitation frequency and signal processing, it is possible to visualize e.g. certain layers of polymer backsheets or cell connections within a few minutes (figure below).

A particular strength of the described method is the detection of defects such as cracks or air bubbles, as the acoustic waves are reflected strongly from such interfaces, which results in clear signals. This approach is already applied to analyze defective backsheets in many of our projects with industrial partners. Cracks caused by weathering in individual layers of the backsheet can thus be detected without destroying the materials, even if they are not visible from outside (figure below). In addition, the imaging method can allow conclusions to be drawn about the specific load from the spatial distribution of such cracks. In the illustrated case, we were able to prove that the degradation was related to a higher UV intensity between the cells. In other cases, cracks were located predominantly behind busbars, which indicates a specific effect of mechanical stress caused by diurnal cycles.

We are currently cooperating with the manufacturer, PVA TePLA, to investigate further optimization of the method and extension of the temperature range in the "ZeitnaH" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).





Scanning acoustic microscope image of different module layers. Inset: Internal cracks in the backsheet.

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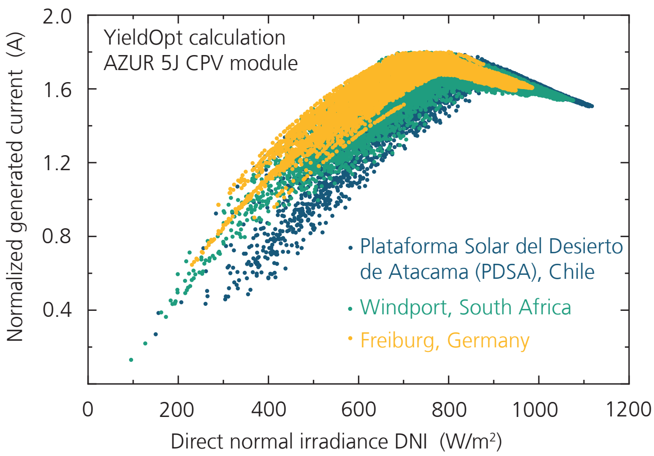
Integration of Solar Cells with Five pn Junctions in Concentrator Modules

In concentrator photovoltaics (CPV), sunlight is focussed onto small solar cells by inexpensive optics. The ratio of the solar cell area to the module aperture is thus reduced by the concentration factor (> 500) and complex multi-junction solar cells with highest efficiency can be used. Up to now, a solar cell with three pn junctions was commonly used. Our project partner, AZUR SPACE Power GmbH, is now introducing a new five-junction solar cell, which promises to deliver even higher module power.



Generated current of a CPV module normalized to the irradiance DNI of 1000 W/m² in different locations (Chile, South Africa and Germany).

In addition, this solar cell is suitable for mass production. We are working together with AZUR SPACE Solar Power GmbH in the "QuintuMod" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). In the project the five-junction solar cell is integrated into the C3PV module from AZUR SPACE. At Fraunhofer ISE, we are investigating the performance of these modules by measurements on our outdoor test tracker in Freiburg. We determine the performance under CSTC conditions (concentrator standard test conditions; 1000 W/m², AM 1.5d spectrum and 25 °C solar cell temperature) according to IEC 62670-3. We have already determined a very good efficiency of 35.3 % at CSTC for the new module.

However, it is not the maximum achievable efficiency under CSTC conditions which is decisive for economic success, but the electricity yield over the service life. In real operation, the temperature of the solar cell is usually higher than 80 °C. Within the project, the solar cell structure will thus be adapted by AZUR SPACE such that all sub-cells of the five-junction solar cell generate the same current at the operating temperature and thereby achieving the highest total power. At Fraunhofer ISE, we are developing measurement routines further so that both the external quantum efficiency (EQE) and the solar cell lens unit can be measured at high temperatures.

In addition, the environmental conditions at the specific location of a CPV installation influence the electricity yield. The graph (left) shows the current that we have calculated for different irradiance conditions, applying the "Yieldopt" model we developed in house. The different locations feature different distributions, which are explained by variation in the solar spectrum. Within the project, we at Fraunhofer ISE are investigating this influence on the electricity yield and how it can be taken into account.

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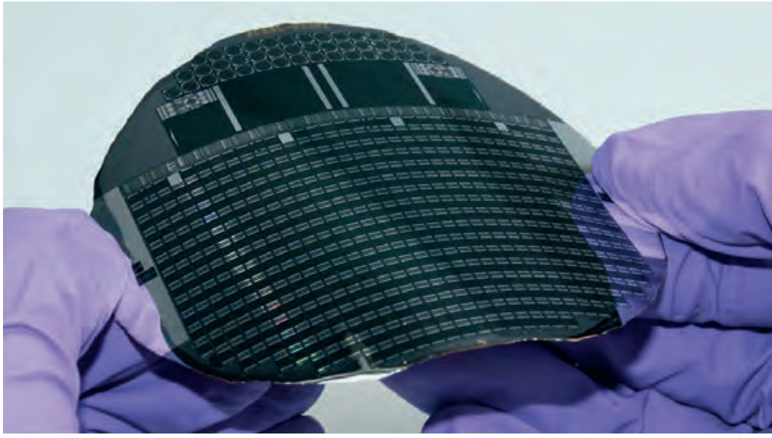
Tracking unit at Fraunhofer ISE to characterize the concentrator PV modules from AZUR SPACE Solar Power GmbH.

Record for Photovoltaic Light-to-Electricity Conversion: Photonic Power Converter with 68.9 % Efficiency

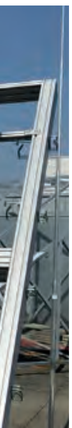
In addition to their classic applications on roofs and in power plants, solar cells can also be used for optical power transmission. Monochromatic laser light is transmitted through free space or via optical fibers to the consumer and converted there using special photovoltaic cells, so-called photonic power converter, into electric power. This "power-by-light" technology is now used in various application areas. The inherently electrically insulating connection offers advantages, for example with respect to electromagnetic compatibility and for protection against lightning and explosion. Energy transmission can also be combined with optical data transfer in a single system. Application examples range from fiber-coupled sensors to monitor the condition of wind-power turbines, through wireless power supply for implants, up to aerospace applications or in wireless power supplies for the Internet of Things.

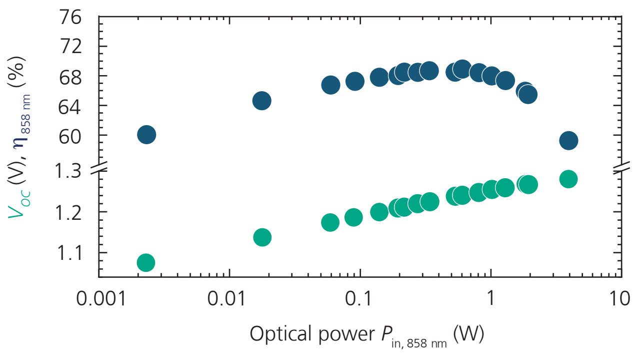
Because of the wideband solar spectrum, the efficiency of solar cells is limited by thermalization and transmission losses. The former results from the excess energy of high-energy photons compared to the bandgap energy of the absorber material. The latter results from the transparency of the semiconductor material for long-wavelength radiation. In photonic power converters, these losses can be almost completely avoided by optimal tuning of the bandgap energy of the absorber and the photon energy of the laser.

Last year, we succeeded in achieving a new record value for photovoltaic conversion efficiency with a GaAs-based photonic power converter. In addition to the tuning of the laser wavelength and the absorber material mentioned above, we followed a thin-film approach and further developed it in the "Lightbridge" project funded by the German Federal Ministry of Education and Research (BMBF). The back surface of a cell structure, which was only about 2 µm thin, was coated with an electrically conductive reflector. This allowed optical resonance effects on the one hand and so-called photon recycling on the other to be exploited. For the absorber of the cell with an area of 0.054 cm^2, a n-GaAs/p-AlGaAs heterostructure was developed with particularly low recombination losses. Using this cell, we demonstrated an efficiency of 68.9 % for the first time, for conversion of monochromatic light with a wavelength of 858 nm at an irradiance of 11.4 W/cm^2 into electric power.



Flexible 4" wafer with GaAs-based photonic power converters processed as thin-film technology.





The measured performance parameters, the monochromatic efficiency $\eta_{858\,nm}$ and the open circuit voltage V_{OC} of the GaAs-based record cell with an area of 0.054 cm², plotted as a function of the optical power at a wavelength of 858 nm.

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Interactive Building Monitoring Tools for the Energy Transition

Decarbonization of the building sector demands new energy supply and operating concepts, which take account of the increased demands of recent years with regard to systems technology, energy-relevant performance and user comfort. Technical monitoring has thus become noticeably more important as a service for the building sector to support quality management for buildings and is increasingly being included in new building projects and building renovation.

Technical monitoring makes energy-efficient building operation feasible that is suited to its function and requirements. The central regulations for public buildings in Germany are found in the guidelines for technical monitoring of the working group for mechanical and electrical engineering in state and municipal administration (AMEV-TMon). At the same time, an ongoing trend toward the planning and implementation of building projects according to the method of Building Information Modeling (BIM) can be observed. It allows interconnected and digitally supported cooperation among all trades and professions over the life cycle of a building, from planning through construction to operation. However, up to now there has been a lack of suitable tools to compare the available BIM information to the requirements of AMEV-TMon and to support the commissioning, running-in and energy-relevant optimization of systems on the basis of measured data.

MoTive simplifies the planning and implementation of an intelligent technical monitoring system, for example for room ventilation systems such as shown in the illustration.

One goal of the "BUiLD.DIGITiZED" research project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), is to develop a tool which digitally supports the commissioning of building plant on the basis of BIM information. Within the research project, Fraunhofer ISE developed the "MoTive" (MonitoringInteractive) tool and tested it with several demonstration projects.

MoTive extracts relevant information on sensors and actuators from BIM planning documentation and connects this with data sets of test quantities from AMEV-TMon. The information from different sources such as files of the Industry Foundation Classes (IFC), test quantities according to AMEV-TMon or data point lists from building automation are combined in a web-based application. On this basis, MoTive offers various functionalities to support the planning and implementation of a technical monitoring system. For example, the current version of the software automatically generates a list of systems and an interactive system scheme and allows all relevant semantic and topological information on the systems, sensors and actuators to be accessed. In this way, connections can be recognized which monitoring service providers otherwise have to introduce and test tediously by hand, which greatly simplifies the commissioning of building plant and its operation management processes. During the further course of the "BUiLD.DIGITiZED" project, the functionality and applicability of the tool is to be investigated with partners from the building sector when commissioning the new laboratory building of the University of Applied Sciences in Offenburg.

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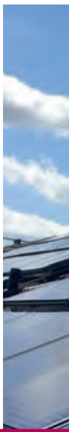

Heat Pump Systems in Existing Apartment Buildings

To achieve the climate protection goals in the building sector, not only must the energy-relevant quality of building envelopes be improved but also the heat supply must be switched to low-CO_2 technologies as quickly as possible. Heat pumps, which extract heat from their surroundings and convert it by application of electricity to a usable temperature level, are particularly suitable.

Due to the continually increasing share of renewable energy in the German electricity mixture, heat pumps already make an appreciable contribution to decarbonization. Their application in new buildings is now standard but the potential in the existing building stock has not yet been exploited. Fraunhofer ISE has already demonstrated that heat pumps can also be applied efficiently for existing free-standing and semi-detached houses. However, they are still a rarity in existing apartment blocks or terrace houses. Thus, Fraunhofer ISE is cooperating with industrial partners to develop novel solutions for sustainable heat supplies of existing apartment blocks in the "LowEx-Bestand" project that is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

One approach addresses low-threshold adaptations to the building to reduce the temperature of heating loops. Technically, heat pump systems are also able to meet demands for high inlet temperatures in the heating system. However, reducing the system temperature leads to higher efficiency. One measure for the efficiency is the annual seasonal performance factor (SPF). Field-test results and simulations demonstrated that the annual SPF improved by about 0.1 with each Kelvin decrease in average heating-loop temperature.

A temperature reduction is often feasible also in existing buildings with radiators, particularly if the heating demand can be reduced by renovating the building envelope. By continuing to use existing, often over-dimensioned radiators, the heat pump efficiency can already be increased significantly with minimal adjustment to the heat emitting system. In the "Smartes Quartier Durlach" project, which was also funded by the BMWK, we followed this approach in existing apartment blocks. In addition, we succeeded in equipping one block with photovoltaic-thermal (PVT) collectors, which supply low-temperature heat as the heat source for the heat pump.

A further apartment block uses a heat pump with a multi-source system, which combines a small field of ground probes with an outdoor air unit. The system hydraulics and controls were developed by Fraunhofer ISE within the "HEAVEN" project, which was also funded by the BMWK.

In an existing apartment block in Adorf, which has not yet been renovated, we gained experience with a hybrid heat pump system. This combines a heat pump with a condensing boiler, applying optimized controls. Initial measurement results show that despite the small dimension of the heat pump (6 kW under standard conditions A2/W35 versus a 28 kW heating boiler), the heat pump supplied between 50 % and 61 % of the space heating load in the months of January and February. After the planned energy-saving renovation of the building envelope has been completed, it is expected that the relative contribution of the heat pump will become significantly higher.

PVT collector field providing low-temperature heat to the source side of a heat pump system in an apartment block in Karlsruhe-Durlach.

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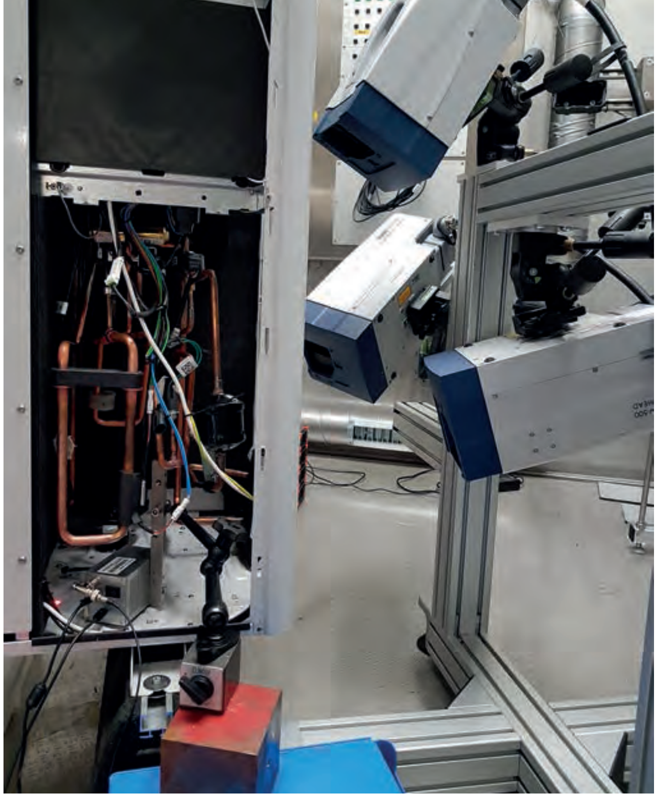
Making Air-to-Water Heat Pumps Quieter

Heat pumps are playing an increasingly important role for future, decarbonized heat generation. This applies particularly for air-to-water heat pumps, which have dominated market sales for about ten years. Modern heating systems of this type are more economic than other types of heat pumps and generate only 50 % of the CO_2 emissions produced by gas-fired condensing boilers – a reduction which will become even greater as the decarbonization of generated electricity progresses. Due to this major gain in importance, innovative solutions to reduce the noise emitted by heat pumps will be demanded for their application in densely built-up areas.

To investigate new approaches to optimize the acoustics of heat pumps, Fraunhofer ISE and Fraunhofer IBP jointly initiated the "WAMS" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Within the project, we have developed methods which allow us to accurately identify and measure the causes of noise. In close cooperation with heat pump manufacturers, we were already able to prepare proposals to improve heat pump heating systems in an early development phase. The focus is on the generators of airborne sound, which primarily comprise the fan and the compressor. The work of Fraunhofer ISE is targeted particularly on the compressor, as appreciable improvements in fans have already been achieved in recent years. Thus, the compressor has often become the dominating source of noise emissions from a modern system.



Structural dynamics investigation of a heat pump with its compressor removed.

But why is a compressor loud? To answer this question, the interaction between primary airborne sound and structure-borne sound must be understood, which is included in the so-called secondary (or indirect) airborne sound. To this purpose, we have developed an experimental method to detect and investigate these quantities separately. They are combined by calculation to give the total quantity of sound and compared to an airborne sound measurement of an unchanged heat-pump device. After subtracting the effects of the measurement chamber and the measurement uncertainty, the difference allows the proportion of the different types of sound to be analyzed. These results on the behavior of individual structures and components provide an important basis for developing quieter heat pumps.

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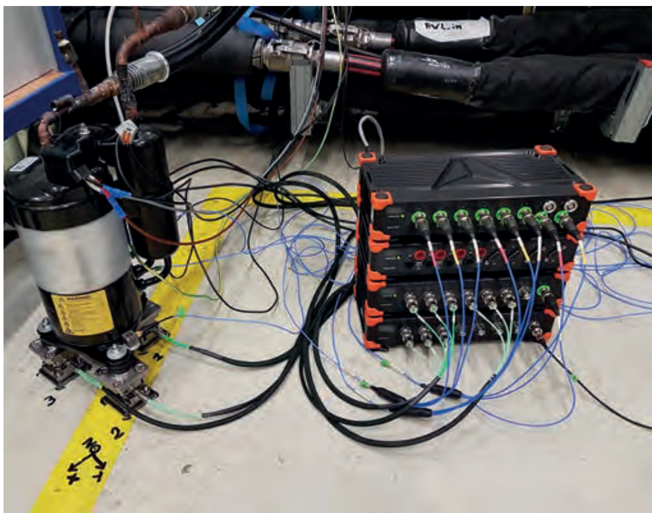
Measurement of the short-circuit force of a refrigerant compressor to evaluate the noise emission of heat pumps.



"*Speed*Coll 2": Service Life Estimation for Solar Thermal Collectors and Their Components

Provision of heat to residential buildings is very significant for the energy transition and the thermal use of solar energy makes an important contribution in this area. In the "*Speed-Coll 2*" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE has cooperated with the "Institut für Gebäudeenergetik, Thermotechnik und Energiespeicherung" (IGTE), University of Stuttgart and 13 industrial partners representing all relevant links in the value chain to investigate the service life and sustainability of solar-thermal collectors, components and materials. The research focussed on applications in diverse climates, including extreme ones, and export markets. In addition, the sustainability of the products was investigated on the basis of their ecological footprints, taking their lifetime into account.

The intensive cooperation made it feasible to examine the degradation processes and the relevant influences comprehensively for the first time. The project built on the "*Speed*Coll" project and encompassed the monitoring and investigation of degradation processes in solar collectors over almost ten years in total – an immense gain in knowledge and a milestone for the industry. For the first time, the results allow the expected lifetime of collectors and individual components to be estimated, depending on various parameters such as high temperatures, UV radiation, humidity or salty atmospheres. By applying the developed procedures for testing, characterization and simulation, we succeeded in establishing relationships between the climatic application conditions and their effect on the properties of the test samples and in providing information on the service life and real aging. On this basis, we have developed test procedures for different regions, particularly for the combination of salt, sand and moisture loads encountered in maritime regions. In this way, the lifetime and thus also the durability of solar-thermal collectors can be ensured in specific climatic conditions and target markets.

The results mentioned above provide the solar industry with valuable information about the anticipated lifetime and possible weak points, and make an important contribution to the development of durable and high-quality solar collectors. Beyond this, the analysis of the collectors and their components at sites with extreme loads (desert climate, corrosive maritime climate, alpine climate, tropical climate) demonstrates that the investigated high-quality products showed no or only slight degradation effects. Their long-term performance in moderate climates, can thus be considered to be certain, even over several decades. The newly developed methods to determine the ecological footprint allow the sustainability of the products to be estimated – and thus also the ecological footprint of the heat that is supplied over the lifetime of the products. In addition, the definition of a neutral reference collector allows individual products to be compared with the current state of the art.

Test site on the Zugspitze, Germany, which represents a cold-moderate alpine climate, with samples from the project.

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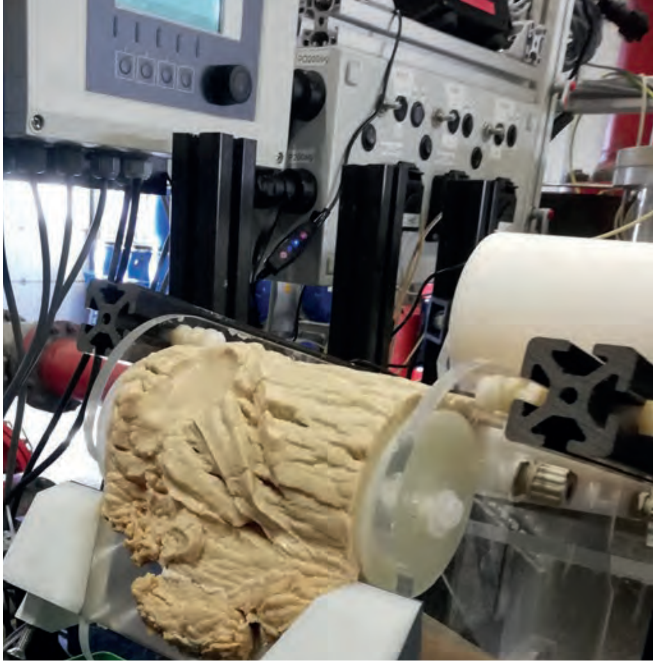
Extraction of Raw Materials from Geothermal Water

Northern Chile is one of the driest regions on earth but it is also the location of extensive geothermal resources. With novel "combined power stations", not only could climate-friendly electricity be generated there in future but also fresh water could be obtained and raw materials could be extracted. Twelve of the raw materials that are globally considered to be "critical", such as rubidium, caesium or boron, can be concentrated and extracted from geothermal sources in this region. The lithium reserves, which are urgently needed to implement the energy transition, are of particular interest. In the German-Chilean "BrineMine" research project, which started in 2019 and is financed by the German Federal Ministry of Education and Research (BMBF), the Chilean resources are being evaluated on the basis of exploration, and extraction technology is being developed and tested in the field.



Continuous discharge of the precipitated products through the conveyor belt filter of the plant.

Test facility in Insheim for the precipitation of extraneous materials such as calcium and silicates and for the concentration of geothermal brine.

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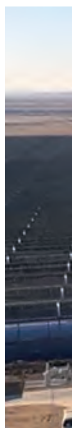
Within the project, Fraunhofer ISE is developing, designing and constructing the systems technology to concentrate the geothermal brines and extract minerals from them (figure to the left). The technology that has been developed for application in Chile is based on a novel combination of different processes: First, the heat from the geothermal brines is used as an energy source to generate electricity, as is already the case. The brine, which has thus cooled to a waste-heat level of about 60 °C and still has a low concentration of salts, is then fed through a chemical precipitation reactor, where extraneous materials such as silicates are removed and the brine is then cooled further (figure above). The consistency of the precipitate sludge depends on the chosen precipitation conditions. At a temperature level of app. 25 °C, preliminary concentration is then achieved with a pressure-driven reverse osmosis system. At the same time, the largest share of fresh water is obtained. Then the concentrated brine is further concentrated by membrane distillation up to the saturation limit. The waste heat provides the thermal energy needed for this process. Finally, minerals such as lithium can be extracted in the following process.

Extraction of raw materials from geothermal brine is of increasing economic and strategic interest with regard to raw material supplies, not only for Chile but also for Germany and other countries. For instance, Fraunhofer ISE, together with "BrineMine" project partners, successfully tested a first experimental system in the geothermal power station run by "Pfalzwerke Geofuture" in the Upper Rhine rift valley near Insheim and thus convincingly demonstrated the function of the new processing chain (figure to the left). In cooperation with our industrial partners, we are now planning the next step, namely the construction and commissioning of the experimental plant at a geothermal location in Chile, with the goal of subsequent upscaling and commercialization.



"SinoTrough" – an Optimized Parabolic Trough Collector for the Chinese Energy Market

In recent years, the demand has risen steeply for renewable electricity sources which are available day and night and can compensate fluctuations in the electricity grid. This development can be observed around the world but is particularly relevant for China. Solar-thermal power plant applying concentrated solar power (CSP) with thermal storage offer a sustainable solution to this problem.

In the German-Chinese "SinoTrough" project, which is funded by the German Federal Ministry of Education and Research (BMBF), Fraunhofer ISE is working together with sbp sonne gmbh and Royal Tech CSP Limited on a collector system that is to further increase the efficiency and reliability of the technology and simultaneously reduce the production costs. The goal is to develop an innovative parabolic trough collector which meets the requirements of the Chinese energy system. The project thus specifically takes the required robustness to the harsh environmental conditions in North-West China and the conditions of the Chinese market into account. Fraunhofer ISE is thus investigating not only technical questions but also socio-economic acceptance and is actively involving the relevant communities and interest groups in the process. The study offers further important perspectives to investors and political decision-makers, allowing them to analyze and understand the value of CSP projects.

Against this background, two online surveys are currently being conducted: One study on market acceptance is addressed to the main actors in the CSP delivery chain in China from planning, procurement and construction as well as to component manufacturers and investors. The other questionnaire on acceptance is directed to the residents of Inner Mongolia, Gansu and Qinghai Province. The method of input-output analysis and the "Jobs and Economic Development Impacts Model for Concentrating Solar Power" serve as the basis for evaluating the potential economic effects of the project.

The primary analysis reveals that a 50 MW demonstration system with SinoTrough technology could create 243 jobs per year – 44 of them locally, 77 in the delivery chain and 122 as follow-on effects during operation. During the 25-year operating lifetime, the system could generate a total of around 432 million USD in economic performance.

To smooth the path for a higher proportion of renewable energy in the future energy system, we have analyzed the preconditions in a model region of China. The potential of this technology, which can generate electricity as required from thermal storage units, to strengthen the Chinese electricity grid on the long term was determined by applying the "Entigris" and "ColsimCSP" simulation tools of Fraunhofer ISE. By evaluating the technical potentials, we identified suitable Chinese areas for the installation of CSP, which are predominantly located in north-western and northern regions. In addition, we quantified the need to expand the inter-regional distribution grids and the installed capacity for renewable energy in a reference scenario and a scenario with a high proportion of renewable energy.

100 MWe parabolic trough plant in Urat, Inner Mongolia, China, developed by sbp sonne gmbh and Royal Tech CSP Limited.

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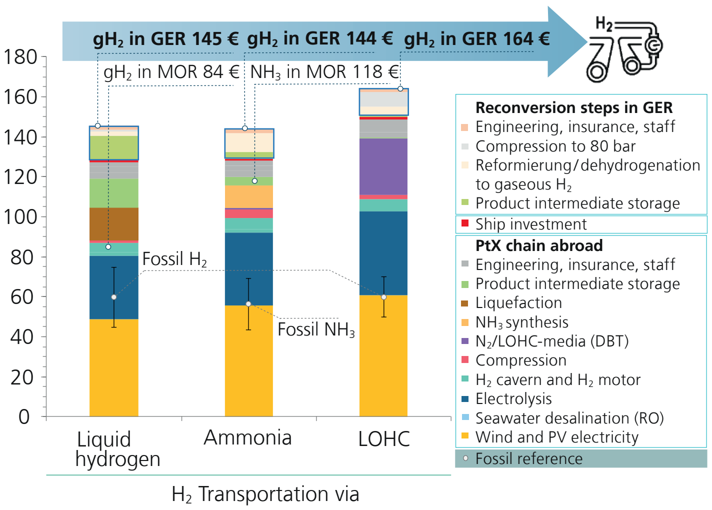
Economic and Ecological Evaluation of Large-Scale Hydrogen and Power-to-Liquid Scenarios

The generation and supply of hydrogen-based fuels by the Power-to-X approach (PtX) is a key step toward decarbonization of national economies around the world. Current energy system analyses predict a PtX demand of several hundred terawatt-hour magnitude by 2040 or 2050, not only for Germany but for numerous national economies around the globe. Particularly the petrochemical and steel industries, but also heavy transport, shipping and aviation will depend strongly on these imported synthetic fuels. For this reason, it is essential to make the establishment and utilization of PtX generation and transport chains as cost-effective and environmentally friendly as possible, as well as being socially just.



Provisioning costs (production and ship transport) in Germany (GER) for "green" liquid hydrogen (at 80 bar pressure) imported from Morocco (MOR) via three transport options in 2030.

At Fraunhofer ISE we conduct holistic life cycle assessments (LCA) of different PtX scenarios with a clear focus on economy and ecology. The multi-facetted analyses range from detailed well-to-wheel analyses for novel synthetic fuels, through techno-economic investigations of large-scale PtX concepts at globally distributed sites, to life cycle assessments (LCA) of future energy systems.

In a current investigation, we compare the efficiency and the provisioning costs for different hydrogen transport scenarios in 2030 with hydrogen generation in Morocco and subsequent ship transport to Germany. The study considers transport options for liquefied hydrogen, ammonia and liquid organic hydrogen carriers (LOHC), among others, as well as fully decarbonized processes. To avoid fossil fuels, the entire PtX chain is powered by renewable energy. In addition to GIS-based location analyses, the "PtX-Pro-Sim" toolbox developed at Fraunhofer ISE was used for the assessment. It allows PtX paths to be simulated with high temporal resolution and optimized with respect to system dimensioning and operation.

The results show that the generation costs for renewable electricity from wind turbines and PV plants and the costs for the considered PEM electrolysis (420 – 480 MW_{el}) represent the largest proportion of the final hydrogen provisioning costs in all scenarios. By contrast, provision of water by seawater desalination applying reverse osmosis does not represent a relevant cost factor. Rather, factors such as the highest possible number of full-load hours for the renewable energy, an efficient electrolysis process, series production of hardware components for electrolysis and flexibilization of synthesis processes proved to be of central importance for further significant reductions in the PtX production costs.

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Synthetic energy carriers obtained via the Power-to-X pathway represent a key step towards highly decarbonized global economies.

Hydrogen Quality Measurement under Real Conditions at Refueling Stations for Cars

Calibration stand (Offenburg University of Applied Sciences) for calibrating and testing flow sensors at the hydrogen refueling station at Fraunhofer ISE.

As an environmentally friendly fuel, hydrogen is an essential component of the transport transformation. Since 2012, Fraunhofer ISE has owned and operated one of the first hydrogen refueling stations in Europe. It is a research platform which is simultaneously available to the public as a refueling station. A further special feature of the refueling station is our own electrolyzer to generate hydrogen. With this facility, Fraunhofer ISE can now draw on experience from more than ten years of construction, operation and maintenance of the refueling technology, which has played a role in numerous projects, including those to test components: Our hydrogen refueling station offers a unique test platform for trials under real conditions. Tests can be carried out not only during normal operation of the refueling station but also without public refueling operation, if required. Recently, we tested microfilters in the dispenser and compared the results with analyses from earlier research projects. These filters prevent smallest particles from entering the vehicle's fuel tank and eliminate problems encountered with previous filter generations. Beyond that, we have cooperated closely with the University of Applied Sciences in Offenburg to test several flow sensors, from the prototype phase to the product that can be officially calibrated.

The "HAIMa" research project, which was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), concluded successfully at the beginning of 2021. Within the project, we tested a fundamentally new hydrogen quality sensor under real conditions. The goal of the consortium was to develop a cost-effective, mass-producible, fully automated measurement solution to monitor hydrogen quality according to the SAE-J2719 and ISO 14587-2 standards and to test it under real conditions. A major challenge for the hydrogen purity and the measurement systems is presented by the very low, authorized maximum concentrations of e.g. 0.2 ppm for carbon monoxide. The sensor prototype developed by the Hydac industrial partner and ZeMa gGmbH measures according to the infrared spectrometric principle. To extend the detection limit and identify homonuclear molecules such as nitrogen N2, the sensor takes advantage of the high pressure of hydrogen refueling stations. Measurements under conditions of up to 900 bar provided promising results. To validate the laboratory results, Fraunhofer ISE deliberately contaminated the hydrogen refueling station with foreign gases in two measurement campaigns and compared the results measured by the sensor with the measurement results from an external analytical laboratory. Although the results showed deviations between real conditions and laboratory measurements, they were so promising that the prototype is now being further developed by the industrial partner.

Hydrogen quality sensor (right) connected to a 900 bar high-pressure tank of the hydrogen refueling station (left).

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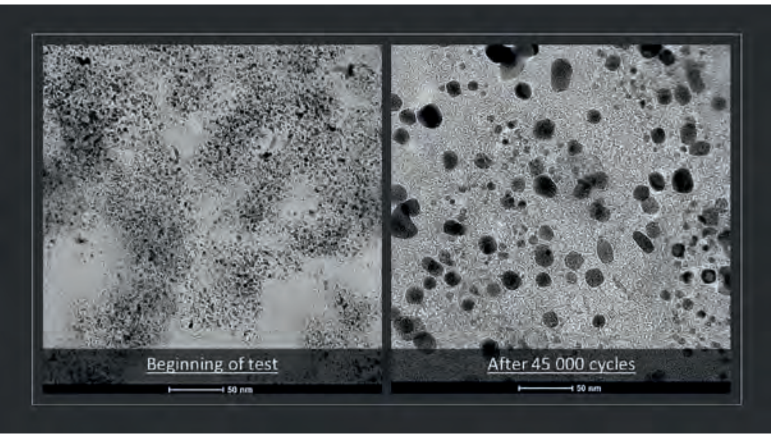
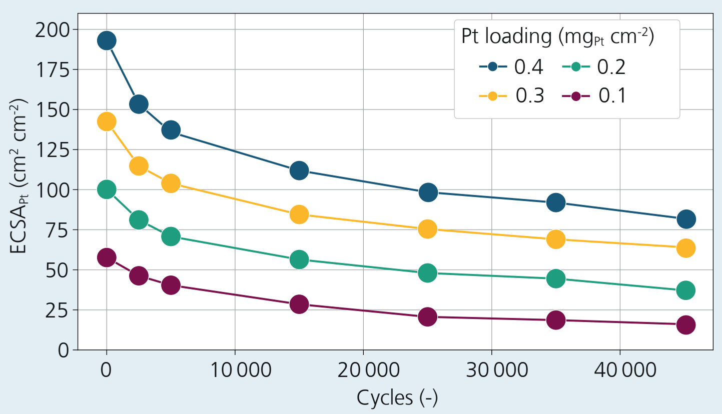
Influence of the Platinum Loading on the Long-Term Stability of Fuel Cells



TEM images of Pt nanoparticles in a non-degraded cathode (left) and a cathode that has degraded during 45 000 potential cycles (right).



Change in ECSA over 45 000 potential cycles between 0.6 V and 0.95 V for different platinum loadings.

The long-term stability of automotive fuel cells is a focus of current research due to their dynamic operation mode. The loss of platinum in its function as a catalyst is decisive for determining the decrease in performance over the operating life of a cell.

Within the "OREO" project, which is funded by the German Federal Ministry for Transport and Infrastructure (BMVI), we at Fraunhofer ISE have investigated the influences on catalyst degradation in detail. We produced membrane electrode assemblies (MEA) with different cathode loadings between 0.1 and 0.4 $mg_{Pt}cm^{-2}$ and characterized their performance and stability electrochemically. As part of the characterization, an accelerated stress test was applied, in which the cells were subjected to 45 000 potential cycles in the critical operating range between 0.6 V and 0.95 V to quantify their stability. Numerous electrochemical methods were applied to do this, which allowed conclusions to be drawn on the performance under different operating conditions and on the active platinum surface area, the proton transport and oxygen diffusion as a function of ongoing degradation.

The graph shows the change in the electrochemically active surface area (ECSA), which decreases as the number of cycles increases for all measured platinum loadings. The causes are platinum particle growth by Ostwald ripening i. e. the dissolution of platinum from small particles and its redeposition on large particles, as well as a diffusion-driven migration of platinum ions out of the electrode. Comparing the different curves, the relative losses of the ECSA prove to be greater for low loadings, as the diffusion-driven loss is then relatively higher.

In cooperation with the University of Connecticut, the ECSA loss was analyzed by an imaging method based on transmission electron microscopy (TEM). The particle size distributions determined from all images showed more strongly growing particles for lower platinum loadings. Furthermore, the increasing diffusion-driven loss with decreasing platinum loading was confirmed by element analyses of the surface.

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C³-Mobility – Climate-Neutral Fuels for the Transport Sector of the Future

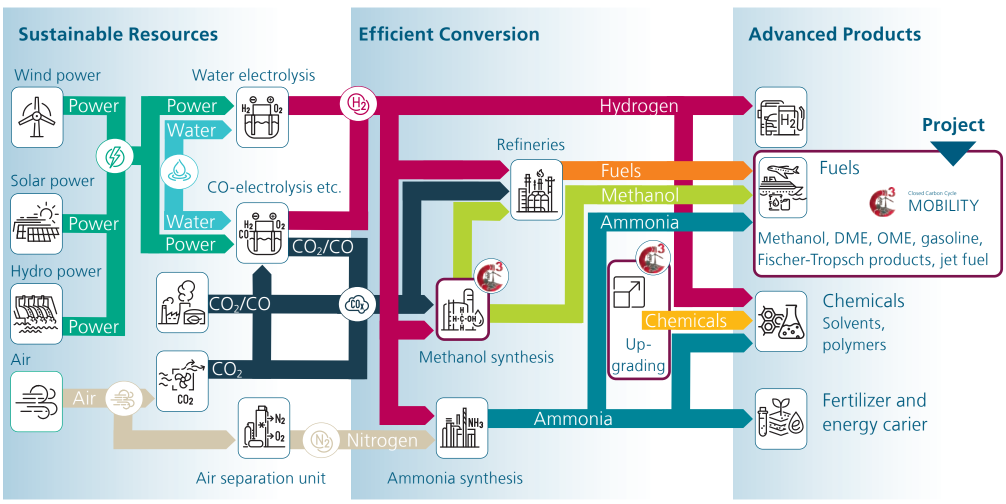
C³-Mobility is one of fifteen research associations within the "Energiewende im Verkehr" (energy transition in transport) initiative of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and unites thirty partners from industry and research. C³-Mobility aims to demonstrate new routes toward CO_2-free mobility with the help of synthetic fuels based on methanol. Synthetic fuels represent an attractive solution for the future of transport, particularly for long distances and large volumes.

The CatVap® prototype was operated with synthetic fuel to reduce CO_2 and secondary emissions and enable nearly zero-emission mobility.

The research project focuses on processing methanol into new, electricity-based fuels for petrol and diesel motors, such as long-chain alcohols, ethers or gasoline (methanol-to-gasoline, MtG). The development of new fuel synthesis processes and combustion concepts is accompanied by interdisciplinary investigations on material compatibility, fuel stability, subsequent treatment of waste gases and fuel sensorics. The suitability of the new fuels developed within the project for use in vehicles is tested under real driving conditions. The applications range from cars through light utility vehicles to heavy utility vehicles. A total of eight demonstration vehicles will be constructed. The project results will merge into an integrated evaluation. This takes account of the synthesis routes and the engine technology, including its efficiency and the emission of pollutants, as well as the conformity of new fuels with current legal requirements on fuels and possible fuel blending strategies.

At Fraunhofer ISE, we are investigating the application of the CatVap® fuel-treatment technology in post-processing of waste gas from overstoichiometrically operated motors within a project funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Initially, we analyzed the behavior of synthetic fuels on an oxidation catalyst. We focused on the interaction between conventional fuel and exhaust gas components, as well as post-processing of exhaust gases during cold phases of motor operation. The experiments demonstrated that temperatures exceeding 160 °C at the oxidation catalyst are needed for synthetic ether fuels to prevent toxic formaldehyde from being formed. This temperature can already be reached significantly earlier by introducing the CatVap® system (illustration above) upstream of the oxidation catalyst. In addition, we demonstrated in a cold-start city cycle using an engine test bench that the selective catalytic reduction system (SCR) downstream for nitrogen oxides removal can start operating already 150 seconds after cold start. In reference experiments without CatVap®, 510 seconds were needed. The CatVap® technology thus offers high potential to reduce secondary emissions in accordance with the EURO VII waste gas standards that are planned from 2025 onward.

The Fraunhofer ISE Power-to-Liquids Scheme with red highlighted C³ Mobility project topics.



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Battery Research along the Entire Value Chain

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Among the known concepts for stationary storage, batteries with aqueous electrolytes are of particular interest, including modern, rechargeable zinc-ion batteries. The applied cell chemistry promises low specific costs and high operating safety. The widespread availability of the materials (here: zinc, manganese oxide, stainless steel) also contributes to the sustainability of the technology.

At Fraunhofer ISE, we have achieved pathbreaking advances in understanding the reaction mechanism, particularly in further understanding the decisive role of the pH value in aqueous electrolytes. Building on these findings, we are currently evaluating different electrolyte additives for targeted optimization of the cycling behavior.

In the "INFAB" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we are cooperating with several industrial partners to develop a zinc-ion battery system with aqueous electrolytes. In addition, we have conceived a specific variant of zinc-ion storage technology for application in developing and threshold countries within the "Sprunginnovation – Weltspeicher" competition run by the German Federal Ministry of Education and Research (BMBF) (illustration on the left).

In the final production step, assembled lithium-ion battery cells must be formed and their quality tested in the so-called aging process. Fraunhofer ISE contributes its knowledge for the specification of a production line in production scale for cells in the 21 700 format as well as a research facility for large-scale pouch cells within the "Forschungsfertigung Batteriezelle" project. Cells are thoroughly characterized (illustration below) and their aging is modelled in the battery laboratory of Fraunhofer ISE, both in industrially commissioned projects and in research projects such as the "DDD-Batman" project funded by the BMWK. This is the precondition for developing methods for data-based diagnosis and prognosis of battery cells which can determine the state of health (SOH) of battery cells at any time with great accuracy. Based on electrical and thermal characterization, we develop model-based battery systems for the mobile and the stationary sectors. This includes customized system design and the further development of battery management systems and innovative measurement technology, for example by application of electrochemical impedance spectroscopy in the "SIMBA" project. In the "PLÖPPSS" project, which is funded by the BMWK, we are cooperating with industrial partners to develop a test stand for propagation investigations to make battery technology even safer.

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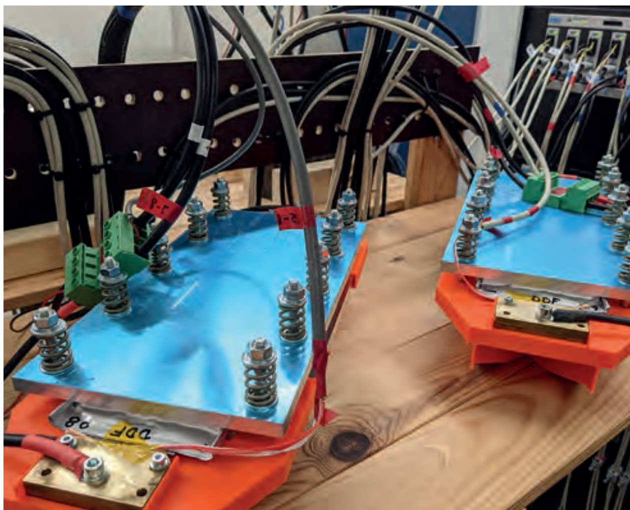
Characterization of lithium-ion cells in the battery laboratory.



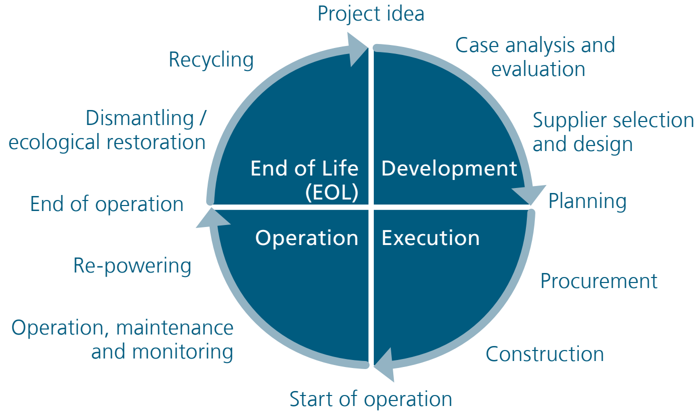
Quality Assurance along the Value Chain – from Battery Cell Production to Application

As the usage of batteries increases, demand is also rising for reliable test procedures to determine their quality and safety. Particularly for electromobility, safe operation of battery systems in combination with high energy density is a decisive factor to further strengthen confidence in the technology and thus contribute to a sustainable mobility transformation.

To this purpose, scientists at Fraunhofer ISE are developing innovative, non-destructive test procedures for quality assurance during the production of battery cells and modules and suitable certification procedures. In the "OrtOptzelle" project, which is funded by the German Federal Ministry of Education and Research (BMBF), we apply sensor-based detection of volume changes to localize defects during battery cycling. Ultrasonic microscopy will be applied in future projects. Our goal is to increase the safety and durability of battery cells significantly by establishing inexpensive, sensitive test methods and detecting manufacturing defects at an early stage. This allows us to identify defects early at the cell level and during system construction and thus to work actively on improving battery technologies and products.

In 2022 in our laboratory destructive tests on battery cells and modules are carried out. There, the safety and quality of all types of test samples are validated under extreme environmental conditions.

However, battery storage systems must prove their quality not only in the laboratory but also during application. They must provide the required performance, completely safely and reliably, under complex operating conditions and during interaction with a variety of components. Independent validation of the quality and performance of energy storage at the system level and their application in the field is extremely relevant for

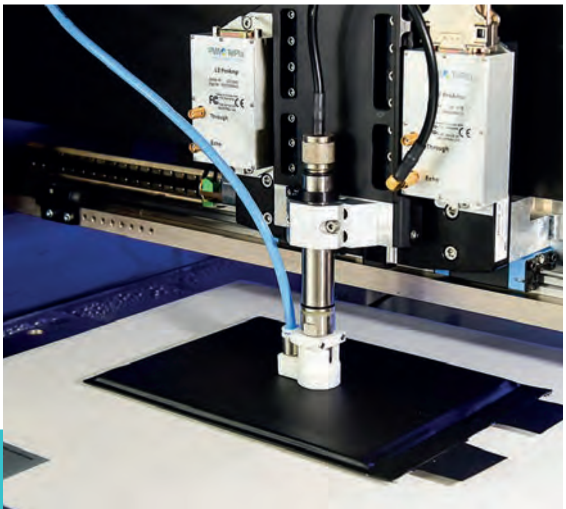


Services offered by Fraunhofer ISE in the field of quality assurance for battery storage systems in field applications.

manufacturers, system installers and investors. These electricity storage systems can range from small, autonomous Solar Home Systems, through electrified mobility, to large MWh storage units for grid stabilization.

We also conduct research of electricity storage components on quality assurance over all life cycle phases. The development of new methods for simulation-based dimensioning of battery storage systems and for optimizing the system design, including all components from the power electronics through to integration of the energy management system are our main focus.

These methods are applied in various areas, for example for optimized integration of battery storage in PV power plants, system tests and validation or during quality monitoring. Our experts prepare high-quality technical and techno-economic analyses, which identify, and if necessary avoid, investment risks at an early phase.



Non-destructive battery cell characterization using ultrasonic waves.

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EnStadt:Pfaff Living Laboratory – a Climate-Neutral Quarter for the Future

3D model of the Pfaff Quarter.

The complexity of future energy systems demands new approaches to solutions in real surroundings. Living laboratories are small-area project contexts, in which concrete concepts and decision aids can be developed, implemented and tested in cooperation with partners from the practice. They make it feasible to comprehensively investigate and optimize the energy system and its components as a function of existing regulations and possible business models. The work is done in close collaboration with the local population.

Since October 2017, the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the German Federal Ministry of Education and Research (BMBF) have jointly funded the "EnStadt:Pfaff" lighthouse project, which is conceived as a living laboratory. The goal is an integrated concept to achieve climate neutrality on the former grounds of the Pfaff sewing machine factory in Kaiserslautern. A mixed-zone quarter for 1 400 residents and employment for 3 200 people is emerging over an area of 18 hectares. Eight partners from commerce and science are working together under the direction of the City of Kaiserslautern to ensure that the quarter is fit for the future. Fraunhofer ISE is responsible for the scientific leadership.

The prerequisite for achieving climate neutrality is that the city provides an appropriate framework, which happens essentially during the urban land-use planning phase and takes account of both economic and legal aspects. EnStadt:Pfaff is accompanying the process with scientific expertise and has prepared pathbreaking concepts for the energy supply, mobility and information and communications technology. On this basis, compulsory solar usage in combination with obligatory roof greening was incorporated into the land-use plan for the first time in Germany. The heat supply is based on industrial waste heat from a neighboring foundry. To keep the number of cars low in the quarter, parking by-laws were passed that make it feasible to build mobility stations.

For the implementation phase, Fraunhofer ISE is developing technology within EnStadt:Pfaff such as an agent-based energy management system based on block-chain technology. Furthermore, the practical suitability of battery technologies will be investigated and aesthetically appropriate, highly efficient PV façade and charging infrastructure for electric vehicles will be designed and constructed. Digitalization plays an important role for climate-neutral quarters both during the planning phase and also when services are provided to future residents and users. To support this, we are developing a digital data platform and a 3D model of the quarter.

With its "sheltered space", the "EnStadt:Pfaff" project offers ideal conditions to test technical, economic, social and regulatory innovations and processes. The interactions between these aspects will also be investigated by Fraunhofer ISE as part of its accompanying sociological work. To this purpose, we are preparing a tool which allows new technologies to be evaluated with respect to living quality. How higher requirements on climate protection affect the behavior of potential investors in a quarter is another question which should be answered.

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Artificial Intelligence for Grid Operation and Grid Planning

Visualization of generated power in the control room of the Digital Grid Lab.

Electricity distribution grids must fulfill new supply tasks in future. Grid operators are thus presented with the challenge of having to enter data for a large number of generators and consumers into their data banks so that they can be taken into account during grid operation. In addition, electric vehicles, being mobile consumers, regularly change their connection point and thus also their effect on the electricity grid. At the same time, the distribution grids are not completely digitalized and can be monitored to only a limited degree due to their complex structure. This is the starting point for procedures to estimate the state of the system, to generate important data for grid operation and grid planning.

By applying artificial intelligence, Fraunhofer ISE is developing new algorithms to improve the classic methods for state estimation. So-called "graph neural networks" (GNNs) are applied. The main advantage of these neural networks is that they make use of structural information via the so-called adjacency matrix of the grid topology during the training process and connect it intelligently with widely diverse data sources. In this way, a good state estimation of the grid can be achieved with only a few data points. To operate the grids, we are developing and testing procedures to recognize new consumers in the "AI4Grids" project, which is funded by the German Federal Ministry of Education and Research (BMBF).

Beyond this, the data gained are helpful during grid planning. In the "StraZNP" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the new equipment is being used in combination with generated time series to determine a new supply task and to plan an optimal grid for it. Together with different operators of distribution grids, we are carrying out automated planning of a target grid that spans different voltage levels and cost-optimizes the integration of the new connection client. The goal of this work is to better estimate the future load on the grids by applying the new procedures and to support the grid planners thereby.

Functional and validation tests of the previously described procedures are necessary before they are applied in practice. For this reason, Fraunhofer ISE operates its Digital Grid Lab, in which we implement digital twins of electricity grids on modern hardware-in the-loop computers. Coupled with a control room and power amplifiers, a realistic system environment is available here for integration tests.

Visualization of the grid state in an example of a distribution grid with newly connected electric vehicles, which are detected by state estimation.

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Extremely Compact Inverter for Direct Connection to the Medium-Voltage Grid

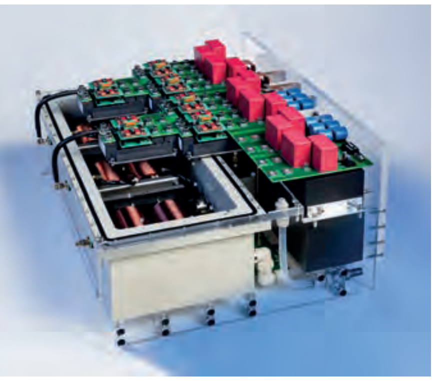
As the energy transition proceeds, expansion of the electricity grids becomes increasingly important. More and more regenerative electricity generators and electricity storage units are connected to the grid. Power electronics plays a decisive role in this process, as it is needed to connect these systems to the grid. Besides pure input and output of electricity, the power electronics must also carry out further grid-supportive tasks. Within the "SiC-MSBat" joint project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), researchers from Fraunhofer ISE, together with other partners, have now developed an extremely compact inverter for direct input into the medium-voltage grid and successfully taken it into operation.

At present, inverters usually feed electricity into the low-voltage grid. They are then connected to the medium-voltage grid via large 50 Hz transformers. The application of innovative transistors of silicon carbide (SiC) with a very high blocking voltage now allows the inverter to be connected directly to the medium-voltage grid. Due to their high control dynamics, SiC inverters can take on grid-stabilizing tasks and can function as active grid filters, for example. Furthermore, very high power densities can be achieved with their help.

Within the project, we developed a 250 kW inverter stack to feed electricity into a 3 kV AC grid. Novel 3.3 kV SiC transistors are used in it. These feature much lower power losses than comparable silicon transistors and thus allow the inverter stack to be switched with a frequency of 16 kHz. Compared to state-of-the-art silicon transistors, this corresponds to a tenfold higher switching frequency in this voltage class. The high switching frequency makes it feasible to save on passive components, because these can be dimensioned smaller.

A further special feature of the inverter is its active liquid cooling, in which a synthetic ester serves as the cooling medium. The coolant is pumped through the inverter and cools both the transistors with a liquid-cooled heat sink and the filter inductors, which are mounted in a closed tank. At the same time, it serves as an electrically insulating medium for the filter inductors, which allows them to be more compact.

The inverter was constructed and tested in the Fraunhofer ISE laboratories, and was found to have a very high efficiency of 98.4 % at its rated power. The configuration of the device allows modular connection of several inverter stacks to reach system power values of several megawatts.



A 250 kVA inverter stack with 3.3 kV SiC transistors developed at Fraunhofer ISE.

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Design and testbench for SiC inverter stacks in the laboratories of Fraunhofer ISE.

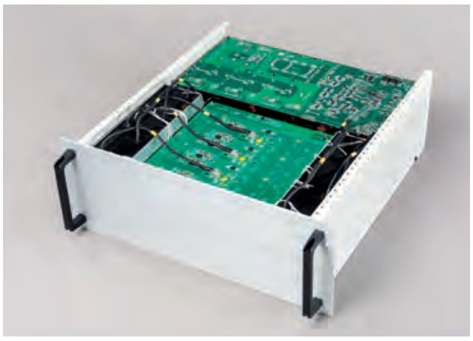
Grid-Supportive Rectifiers for Charging Infrastructure and Electrolysis

As the charging infrastructure in the mobility sector expands, the need for unidirectional electricity rectifiers is increasing. Furthermore, efficient rectifiers have not only become indispensable in the electromobility sector but will also be important in future for the envisaged large-scale generation of hydrogen. Commercially available high-power rectifiers, which convert AC voltage to DC voltage, are predominantly constructed with thyristors today. However, this technology has the disadvantage of negatively affecting the quality of the electricity grid, which demands additional compensatory measures.

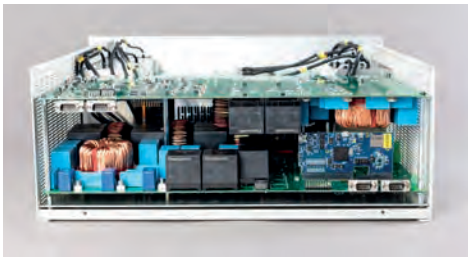
For this reason, Fraunhofer has developed an active rectifier within the "HiPoInd" project which is funded by the German Federal Ministry of Education and Research (BMBF). The goal of the design is to reduce the costs of the converter and simultaneously achieve high performance with respect to efficiency and power quality.

The 3-level PFC topology makes lower losses in the power electronic components feasible and a volume reduction of the associated filter components. Each phase consists of two transistors and four diodes, whereby the costs of the peripheral circuits are reduced in comparison to other 3-level topologies. The output DC voltage is within a range between 600 V and 900 V and the switching frequency is about 30 kHz. Due to the implementation of a novel controller, the total harmonic distortion currents (THDi) in the partial load range are reduced by about 40 % compared to conventional control approaches. Similarly, the constructed topology and the associated control system can provide reactive power as required by currently valid guidelines for grid-connected converters.

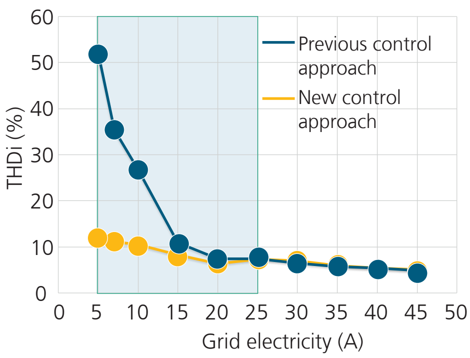
The air-cooled topology has a maximum efficiency exceeding 98 % and is mounted in a 19" rack housing, so that e.g. simple parallel connection in charging stations for so-called high-power charging (HPC) is possible. In addition, there are perspectives for scaling the power of the PFC and applying it in conjunction with electrolysis.



PFC in a 19" rack housing.



2 x 20 kW PFC, modular construction.



THDi improvement under partial load conditions.

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Events in 2022 with Participation of Fraunhofer ISE

January

Batterieforum Deutschland	online	19.01/25.01.2022

February

BatteryWorld 2022	online	16.02.–17.02.2022
Batterieforum Deutschland	online	02.02./08.02.2022

March

FC Expo	Tokio, Japan	16.03.–18.03.2022
LOPEC	Munich, Germany	23.03.–24.03.2022
Batterietagung	Münster, Germany	28.03.–30.03.2022
SiliconPV	Constance, Germany/hybrid	28.03.–01.04.2022

April

SPIE Photonics Europe	Strasbourg, France	03.04.–07.04.2022
OWPT Conference	Yokohama, Japan/hybrid	18.04.–21.04.2022
agra	Leipzig, Germany	21.04.–24.04.2022
CPV-17 – International Conference on Concentrator Photovoltaic Systems	Miyazaki, Japan/hybrid	25.04.–27.04.2022
LASER World of PHOTONICS	Munich, Germany	26.04.–29.04.2022

May

Battery Experts Forum	Frankfurt, Germany	03.05.–05.05.2022
32. Symposium Solarthermie und Innovative Wärmesysteme	Kloster Banz, Bad Staffelstein, Germany/hybrid	03.05.–05.05.2022
PCIM Europe	Nuremberg, Germany	10.05.–12.05.2022
Intersolar	Munich, Germany	11.05.–13.05.2022
4. TeraWatt Workshop	Freiburg, Germany	16.05.–17.05.2022
HOPV 2022	Valencia, Spain/hybrid	19.05.–25.05.2022
16th SNEC PV Power Expo	Shanghai, China	23.05.–26.05.2022
f-cell CANADA	Edmonton, Alberta, Canada	25.05.–26.05.2022
International Energy Workshop 2022	Freiburg, Germany	25.05.–27.05.2022
tandemPV Workshop 2022	Freiburg, Germany	30.05.–01.06.2022
Hannover Messe	Hanover, Germany	30.05.–02.06.2022
EMRS Spring Meeting	online	30.05.–03.06.2022
IFAT	Munich, Germany	30.05.–03.06.2022

June

49th IEEE Photovoltaic Specialists Conference	Philadelphia, Pennsylvania, USA	05.06.–10.06.2022
AgriVoltaics	Piacenza, Italy/hybrid	15.06.–17.06.2022
ICE – International Conference on Electrolysis	Golden, Colorado, USA	20.06.–23.06.2022
Phenology 2022	Avignon, France	20.06.–24.06.2022
E-World energy & water	Essen, Germany	21.06.–23.06.2022
37. PV-Symposium	Freiburg, Germany/hybrid	21.06.–23.06.2022
WHEC	Istanbul, Turkey/hybrid	26.06.–30.06.2022

July

43rd IAEE International Conference	Tokio, Japan	31.07.–04.08.2022

August

ACHEMA	Frankfurt, Germany	22.08.–26.08.2022

September

PSCO-22	Oxford, United Kingdom	05.09.–07.09.2022
Solar Power International (SPI)	Anaheim, California, USA	19.09.–22.09.2022
decarbXpo/Energy Storage/IRES	Düsseldorf, Germany	20.09.–22.09.2022
EU PVSEC	Milan, Italy	26.09.–30.09.2022

October

f-cell	Stuttgart, Germany	04.10.–05.10.2022
Chillventa	Nuremberg, Germany	11.10.–13.10.2022

November

Mission Hydrogen Conference	online	08.11.2022
PVSEC-33	Nagoya, Japan	13.11.–17.11.2022
MRS Fall Meeting & Exhibit	Boston, Massachusetts, USA	27.11.–02.12.2022

All information is based on the data that was available at the editorial deadline. We request your understanding for short-term changes which may be necessary due to the COVID-19 pandemic. You will find the current status under www.ise.fraunhofer.de/en/events-and-trade-fairs

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