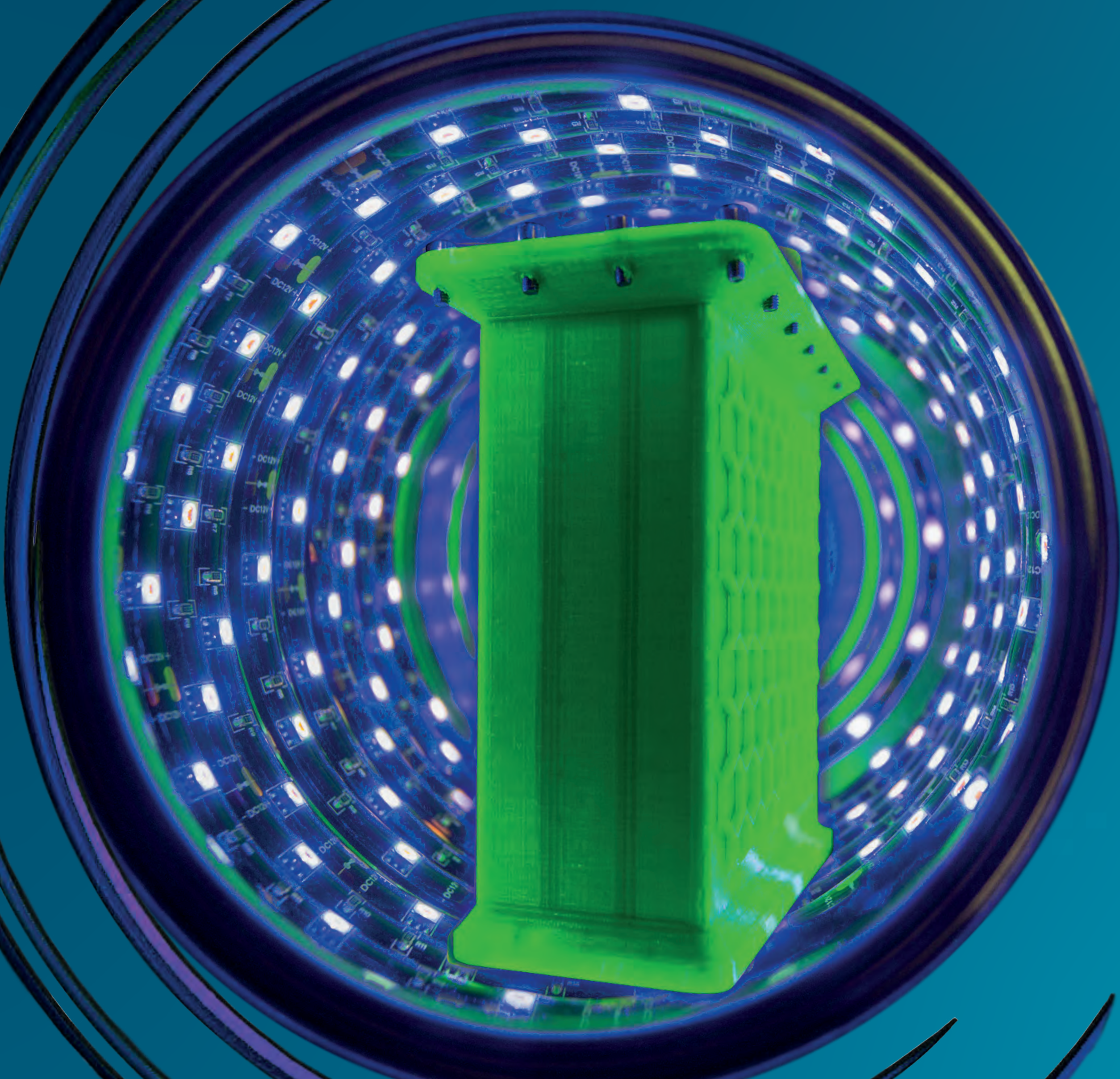
Fraunhofer ISE



Results and Figures

Annual Report 2022/23

The cover photo shows a 3D-printed battery stack with zinc-based battery cell technology and aqueous electrolytes during curing in a UV exposure chamber.

Battery storage is a key element in the transformation of the energy system. At Fraunhofer ISE, we conduct research on zinc-based battery cell chemistries with aqueous electrolytes. They have great potential for cost reductions in active materials and manufacturing processes, assure a high material availability through the use of uncritical materials, and provide increased intrinsic safety and environmental compatibility due to the aqueous electrolyte. In addition to materials research at the cell level, we develop battery stack concepts and work on their configuration and integration into storage systems.

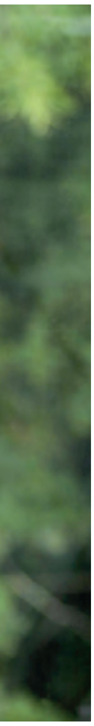
Results and Figures

Annual Report 2022/23

Foreword

During the past three years, we have seen clearly that scientific questions accompany people constantly and have a strong influence on their everyday life. With the beginning of the war by Russia against the Ukraine early in 2022, the focus has increasingly shifted from scientific-medical matters to questions concerning the energy supply and security. We are confronted with the major challenge to cut ties of dependence on fossil fuels and to set the course correctly toward a new, regenerative energy supply, as quickly as possible.

At Fraunhofer ISE, we have always worked on the vision of an energy system which functions without fossil fuels. We possess the necessary know-how to make an important contribution toward an "accelerated energy transition" and to transfer this to the commercial sector. Also, acceptance of the energy transition by society is a topic where we are engaged in intense, interdisciplinary discourse with representatives from politics, business and science, as demonstrated by our symposium entitled "Can the energy transition be implemented sustainably?"



The fact that the energy transition has become a topic of public concern is demonstrated not only by a doubling in the number of enquiries from media representatives: there are also significantly more enquiries from politics and industry relating to conceptual solutions to abandon fossil fuels and achieve greater energy autonomy by using regenerative energy sources. For example, considerable attention is directed toward heat pumps. Our dependence on China with respect to the PV value chain is now leading to intensive discussions to reestablish a PV industry in Europe. The topic of finding enough surface area for photovoltaics, which we address with our key topic, "Integrated photovoltaics", is also in great demand. At this point, we sincerely thank all of our colleagues for the great dedication with which they apply themselves to these diverse and numerous subjects.

However, the current situation demands not only greater efforts with regard to our research activities, but also a critical analysis of our own energy consumption. The Fraunhofer-Gesellschaft and Fraunhofer ISE must also make their contribution to reaching the energy-saving goals of the EU and the Bundesnetzagentur (German Federal Agency responsible for telecommunications, the postal system and energy). As one of the largest technological Fraunhofer Institutes, the energy demand of Fraunhofer ISE is naturally higher than average. The good progress that we have made in saving energy – particularly regarding heat – is due to the prudent and responsible action by our colleagues in all areas of the Institute.

Last year, we consistently developed our Institute strategy further by formulating our mission and guidelines more concretely and supporting them with short-term, medium-term and long-term measures. They take account of the aspect of "comprehensive sustainability", particularly with regard to efficiency, closed resource cycles, and extending the service life of materials and components, but also our clients' expectations, scientific excellence, quality management, process optimization, networking and cooperation.

In the field of energy systems, the increasing proportion of electricity generated from fluctuating sources demands new solution approaches to guarantee a stable and resilient energy supply. One important strategic pillar in our research activities is thus stationary energy storage, which we address with our key topic, "Stationary battery storage – stability and flexibility in the energy system". In this context, we are particularly pleased that we have succeeded in further extending our research infrastructure also during this past year. After a planning and construction phase lasting several years, we took the first laboratories of our new "Center for Electrical Energy Storage" into operation at the beginning of 2022. In the new building, located in the south of Freiburg, we will carry out research on innovative battery materials and cells along the entire value chain in future. One important focus of our work is to exploit the – still large – optimization potential in the area of lithium-ion technology. Another is the investigation of alternative technologies, such as the zink-ion battery that we have developed further.

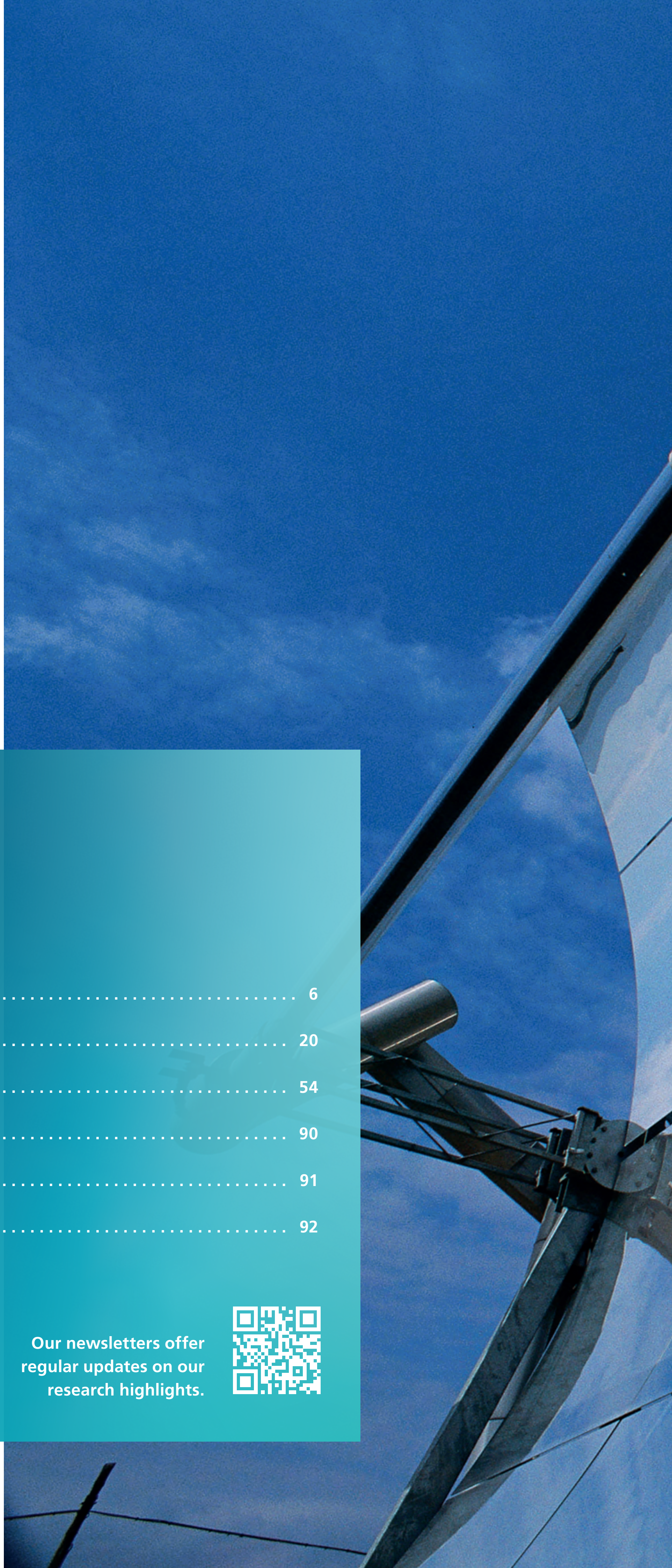
We demonstrated our scientific excellence again in 2022 in many projects and initiatives. One particular highlight was the nomination of the "ChargeBox", a storage-based, extremely rapid charging system for electromobility, for the "Deutscher Zukunftspreis" (German Future Prize) awarded by the German Federal President. In the heat pump technological sector, we achieved an important breakthrough: Together with a consortium of heat pump manufacturers, Fraunhofer ISE developed a standardized cooling circuit which achieves a heating power of 12.8 kW with only 124 g propane – a result with which we are just as pleased as with the development of the most efficient solar cell in the world, featuring an efficiency of 47.6 %.

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

Prof. Hans-Martin Henning   Prof. Andreas Bett

Contents

Our newsletters offer regular updates on our research highlights.



Data and Figures


Fraunhofer
Low Charge Optimizing
Environmentally Friendly Refrigerants for Heat Pumps

Contents









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

Organizational Structure

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

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

- Photovoltaics
- Energy-Efficient Buildings
- Solar Thermal Power Plants and Industrial Processes
- Hydrogen Technologies
- 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)

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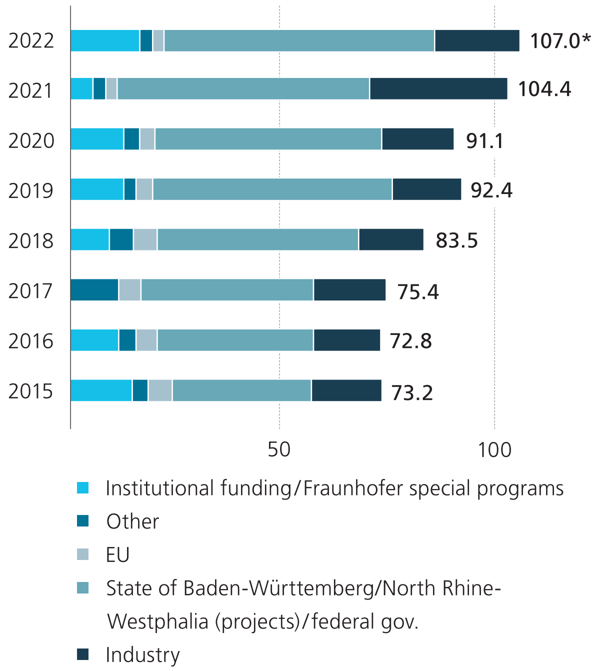
Board of Trustees

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

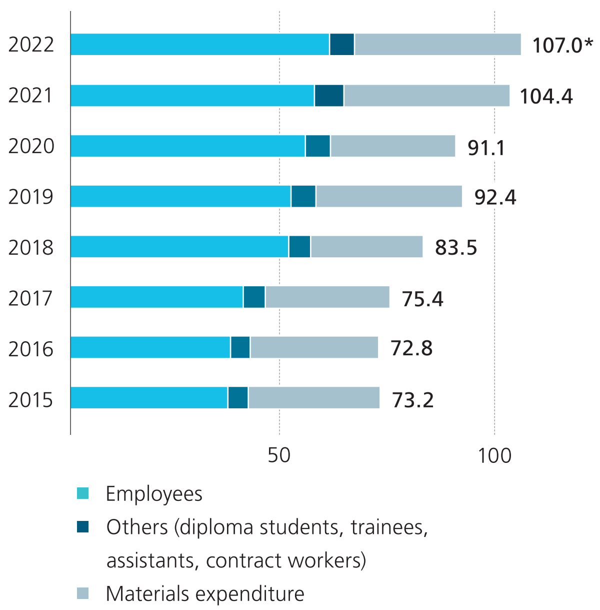
Members of the Board of Trustees as well as external participants of the Board meeting in July 2022. From left to right: Thomas Speidel, Dr. Norbert Schiedeck, Dr. Ingrid Vogler, Dr. Klaus Bonhoff, Prof. Anke Weidlich, Ullrich Bruchmann, Dr. Gunter Erfurt, Prof. Michael Bauer, Jürgen Heizmann, Daniel Etschmann, Prof. Wolfram Münch, Peter Schneidewind, Dr. Stefan Reber, Prof. Anke Weidlich, Sibylle Hepting-Hug.

The Institute in Figures

Income in Million Euros**

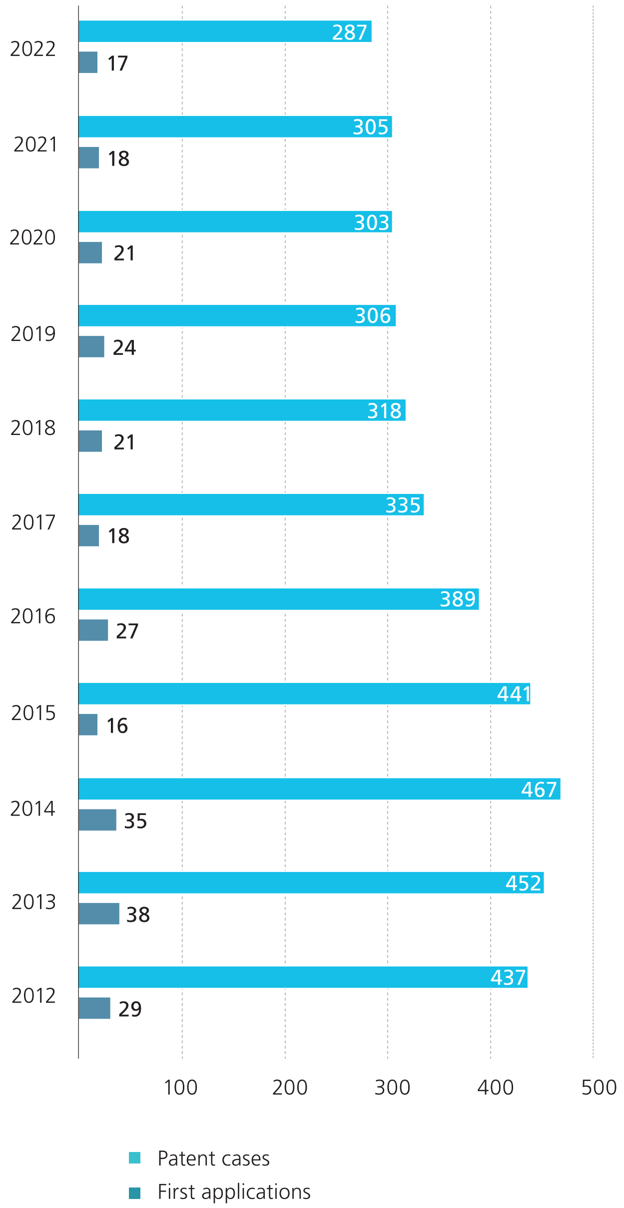


Expenditure in Million Euros**

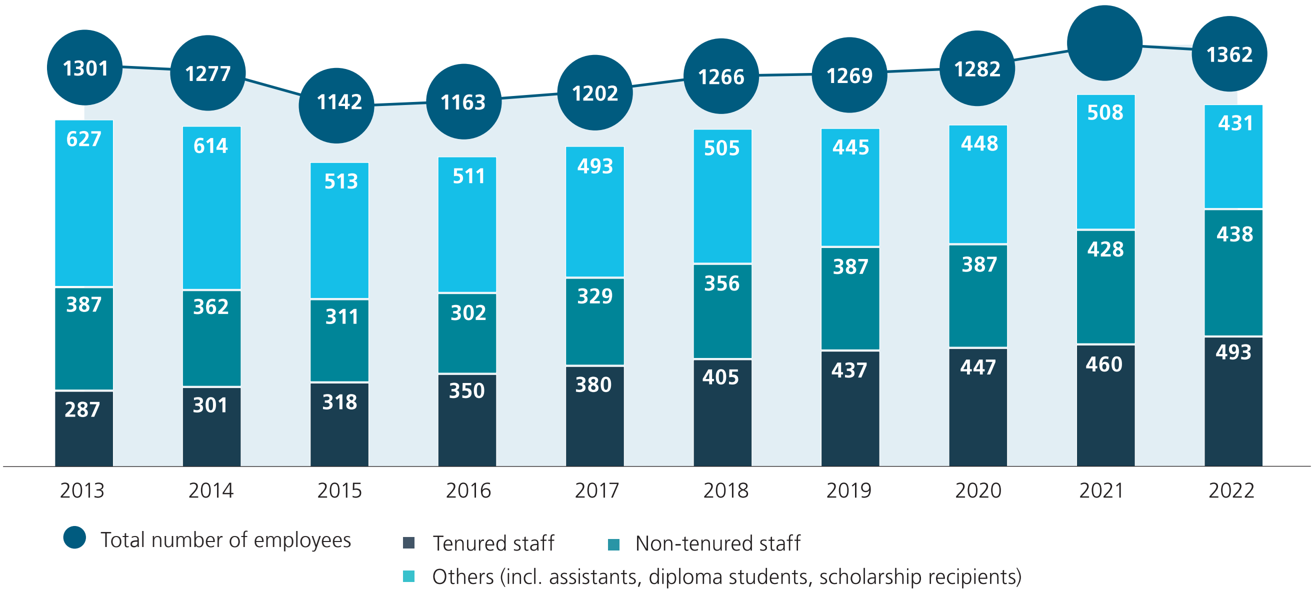


* Preliminary ** Without investments – the total budget in 2022 (incl. investments) totalled 119.3 million euros.

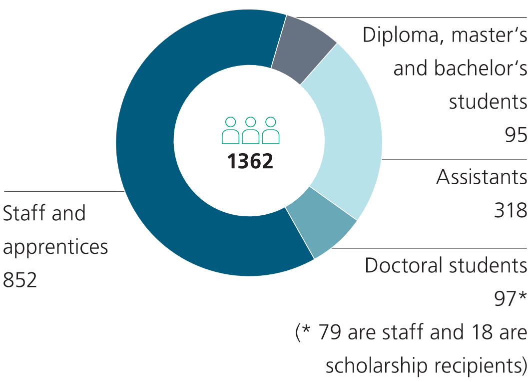
Patents



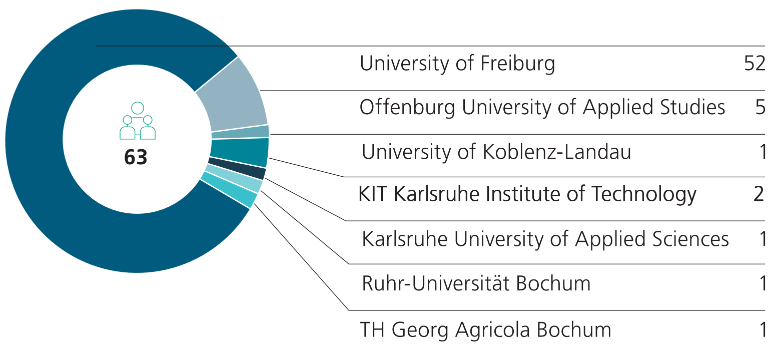
Personnel



Personnel in 2022



Lecture Courses and Seminars



46 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. Our staff of around 1 400 works for an energy supply system which is based on renewable energy sources and is sustainable, economic, safe and socially just. We contribute to this in our research focusing on energy supply, energy distribution, energy storage and energy utilization. We shape the sustainable transformation of the energy system by excellent research results, successful industry projects, spin-off establishment and global cooperation. Parallel to basic funding from the Fraunhofer-Gesellschaft, around 85 % of the Institute's funding originates from contracts for applied research, development and high-technology services. The total budget of the Institute amounted to 119.3 million euros in 2022 (incl. investments).

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 six market-oriented business areas (page 28 ff.). Our research ranges from materials research through component development to systems integration.

Activities

Fraunhofer ISE is equipped with 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 of the highest technical standard encompasses eight R&D Centers and four production-relevant Technology Evaluation Centers (pages 48/49). The Institute also offers testing and certification services in its 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 lifecycle – just as required by the individual contracts, demands and levels of maturity.

Our activities encompass:

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

Corridor of the main building of Fraunhofer ISE.

Eastern aspect of the main building of Fraunhofer ISE.

Cooperation

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

Fraunhofer ISE cooperates closely with the University of Freiburg.

Cooperation with Universities

Fraunhofer ISE places great value on educating future scientists. Currently, 46 employees teach at universities; there are about 200 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 intensive. There is close collaboration with the "Institut für Nachhaltige Technische Systeme" (INATECH – Institute for Sustainable Technical Systems) within the Technical Faculty, which focuses on 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 enterprises, associations and other actors from Freiburg and the surrounding region on the topic of sustainability.

Fraunhofer ISE also participates actively in many other central institutions and activities of the University of Freiburg. For example, we are contributing with our expertise on photovoltaics to the 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, for example. Similarly, we have a tradition of good cooperation 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".

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

Networking within the Fraunhofer-Gesellschaft gives access to a wide spectrum of competence. This approach particularly benefits work on systemic questions.

Groups and Strategic Research Fields

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

The Fraunhofer-Gesellschaft defines Strategic Research Fields so that it can react more specifically to research topics of the future and establish unique scientific-technological emphases. Fraunhofer ISE is represented in a leading role in two of the seven research fields: The Institute Director, Prof. Hans-Martin Henning, and Prof. Welf-Guntram Drossel, Director of the Fraunhofer Institute for Machine Tools and Forming Technology IWU, are the Speakers for the 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

In addition to scientific excellence, the focus of our application-oriented research is the technology transfer to the industry and society. In this context, the Fraunhofer-Gesellschaft has defined eight leading markets 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 energy-economic markets. 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 Energy | Climate | 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) and the Fraunhofer Networks for Intelligent Energy Grids, Sustainability and Hydrogen.

Fraunhofer ISE is the seat of the office of the Fraunhofer Energy Alliance, which brings together competencies in the field of energy research.

Doctoral Theses

Dmitry Bogachuk
"Understanding and Improving Perovskite Photovoltaic Devices with Carbon-Based Back-Electrodes"
University of Freiburg, 2022

Mathias Drews
"Anode Materials and Processing Technologies for Modern Lithium-Ion Cell Concepts"
University of Freiburg, 2022

Benjamin Grübel
"Development of Plating Process Sequences for High Efficiency Bifacial c-Si Solar Cells"
University of Freiburg, 2022

Jan Herterich
"Advanced Characterization of Ionic Motion Effects in Perovskite Solar Cells"
University of Freiburg, 2022

Christoph Meßmer
"Numerical Simulation and Analysis of High-Efficiency Silicon Solar Cells and Tandem Devices"
University of Freiburg, 2022

Matthias Mühleis
"Spectral Shaping for Accurate Solar Cell Characterization"
University of Freiburg, 2022

Florian Nestler
"Dynamic Operation of Power-to-X-Processes Demonstrated by Methanol Synthesis"
Karlsruhe Institute of Technology (KIT), 2022

Jana-Isabelle Polzin
"Poly-Si Based Passivating Contacts for High-Efficiency Silicon Solar Cells"
University of Freiburg, 2022

Regina Post
"Assessment and Application of Defect Characterization via Lifetime Spectroscopy in High Purity c-Si"
University of Constance, 2022

Li Carlos Rendler
"Manufacturing and Analysis of Wave-shaped Wires for Stress-reduced Interconnection of Silicon Solar Cells"
University of Saarland, 2022

Theresa Trötschler
"A Computational Toolbox to Assess VGF-Grown Silicon: Identification and Interpretation of Characteristics for Grain and Defect Development"
University of Freiburg, 2022

The Fraunhofer Center for Silicon Photovoltaics (CSP) in Halle

Fraunhofer CSP in Halle, with a staff of around 100, is a joint institution of the Fraunhofer Institute for Microstrucutre of Materials and Systems IMWS and Fraunhofer ISE. The location was chosen to be near the German Solar Valley in Thalheim. Our focus is on materials research and materials development, including the fields of silicon crystallization and wafer production as well as the rapidly growing field of recycling old photovoltaic modules.

The production of silicon monocrystals and subsequent wafer manufacturing is of central importance for reestablishment of photovoltaic production in Europe. CSP is working on the technological development of ingots with 300 mm diameter and production of wafers with an area of 210 x 210 mm^2 in the G12 format – both topics being areas where Europe has lost know-how and must build up new expertise. In various joint projects (e.g., G12, WaGner, EPINEX), we are searching for promising solutions together with important German companies. The first European wafers in the 210 x 210 mm^2 format were produced at CSP. Our crystallization facilities and multi-wire saws on an industrial scale make R&D activities feasible at production level.

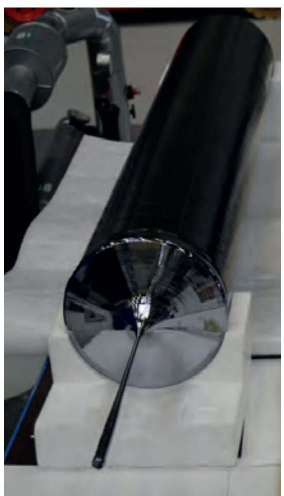
Dismounting and recycling of old, decommissioned PV modules and defect modules is a rapidly growing business area. In the near future, many PV systems will no longer be subsidized and will be dismantled. The returned quantity will soon increase from about 10 000 tonnes annually to more than a hundred thousand tonnes. The German recycling enterprises are faced with the challenge of developing an economically viable recycling process, which can achieve high throughput with high-quality materials separation and material purity. We are thus working intensively on recovering silicon from old modules, extracting silver and copper and returning solar glass to glass melts. Our close cooperation with leading national recycling enterprises and producers of so-called "solar glass" is the basis for commercially relevant research with industrially relevant material flows. The production of Czochralski monocrystalline ingots, of wafers and PERC cells from 100 % recycled silicon last year represents an important step in the direction of a closed cycle and improvement of the sustainability.

With a technical production area of 1 200 m^2 and a crane height of > 6 m (> 11 m near the crystallization facility), CSP is excellently equipped for the installation and operation of pilot systems for materials development. Our crystallization process in three-shift operation allows realistic, industrially relevant test conditions.

In 2022, CSP was recognized for the fourth time in a row as "Germany´s most innovative enterprise". The ranking is prepared by the economics journal, "Capital", together with the market research service, "Statista", and is based on surveys of experts from the sector and innovation specialists.

The façade of Fraunhofer CSP in Halle, viewed from the south.

Czochralski facilities for producing monocrystalline silicon ingots (left) and silicon monocrystals (right).



The Centro para Tecnologías en Energía Solar (FCR-CSET) in Chile

Fraunhofer ISE cooperates internationally with the Centro para Tecnologías en Energía Solar (FCR-CSET) of the Fraunhofer Chile Research Foundation, located in Santiago. It is one of the 15 independent international joint centers of the Fraunhofer-Gesellschaft and works on the research topics of solar power generation, thermal use of solar energy, water purification and application of process heat. In addition, applications for hydrogen production and conversion into its derivates are current topics.

FCR-CSET, with its pathbreaking research and development work in the field of solar energy systems and technology, assumes a leading role in Latin America. At the same time, it can draw on the wide spectrum of competences of the Fraunhofer Institutes in Germany. Technology transfer and adaptation to the specific conditions in Chile, as well as the optimization of system design and operation, are central elements. The foundation of FCR-CSET in 2014 originated in a program to promote the Chilean economy, CORFO, which had set itself the goal of supporting the establishment of international centers of excellence. FCR-CSET works in accordance with the Fraunhofer principle of applied research and transfers its research results to the Chilean industry, to advance the growth of the solar branch there.

Chile is a country which extends over a wide range of latitudes and thus features diverse climatic zones: In the deserts of the north, where the mining industry is located, the solar radiation is the highest in the world. This is one of the best locations to use solar energy for decarbonization and electricity generation. Even in the region around Santiago, the solar radiation is still higher than in the best locations in southern Europe. In the south of Chile, the solar radiation resources are similar to those in Germany. The market has not yet been developed much and the potential for regenerative energy is – in relation to Chile's own demand – enormous.

FCR-CSET is making a significant contribution to Chilean solar research. With annual funding support of 580 000 euros and extrapolated returns of 135 000 euros and 310 000 euros from public and private projects, respectively, Fraunhofer CSET has employed and trained between 25 and 30 scientists and graduates on average each year. At present, there are 25 employees, 85 % of them local and 15 % international.

At present, the emphasis is on demonstration projects for industrial applications based on solar energy for decarbonization and hydrogen production. Three pilot plants for agri-photovoltaics have already been installed near Santiago, to reduce land usage conflicts in urban areas. In 2022, FCR-CSET installed a floating PV system to demonstrate the advantages that result particularly from reduced water evaporation rates. Further demonstration projects with technology transfer from Fraunhofer Institutes in Germany are being prepared. Fraunhofer ISE is the partner Institute for the Chilean Fraunhofer CSET and works closely at all levels together with its Chilean sister.

From left to right: Jucosol project to integrate solar thermal applications into the processed drinks industry; Floating PV system in Paine; Solar metrological station in the Atacama. Desert.

Prizes and Awards

Salma Zouhair
22nd Prize, Nanoge Spring Meeting 2022, presentation "Low Dimensional 2D Perovskite as an Effective Electron Blocking Layer in Efficient (18.5 %) and Stable Hole-Selective Layer-Free Carbon Electrode Based Perovskite Solar Cells", Fundació Scito, 07. – 11.03.2022

Fraunhofer Institute for Solar Energy Systems ISE
World Clean Tech Award, "Visionary CleanTech R&D Institution", CleanTech Business Institute, 15.03.2022

Dr. Johannes Greulich
SiliconPV Award, Paper "Contactless Measurement of Current-Voltage Characteristics for Silicon Solar Cells", SiliconPV 2022, 28.03. – 01.04.2022

Katharina Gensowski
SiliconPV Award, Paper "Filament Stretching During Parallel Dispensing – a Way to Reduce Ag Consumption in SHJ Metallization", SiliconPV 2022, 28.03. – 01.04.2022

Thibaud Hatt
SiliconPV Award, Paper "Plated Copper Electrodes for Two-Terminal Perovskite Silicon Tandem Solar Cells", SiliconPV 2022, 28.03. – 01.04.2022

Dr. Daniel Ourinson
SiliconPV Award, Best Poster Award, "Faster Firing Processes up to 20 m/min Belt Velocity", SiliconPV 2022, 28.03. – 01.04.2022

Jana-Isabelle Polzin
SiliconPV Award, Best Poster Award, "Annealing and Firing Stability of in situ Boron-doped poly-Si Passivating Contacts", SiliconPV 2022, 28.03. – 01.04.2022

Dr. Markus Feifel
Hugo-Geiger-Preis 2021, doctoral thesis, "Hocheffiziente III-V-Mehrfachsolarzellen auf Silicium" (High-Efficiency III-V Multiple-Junction Solar Cells on Silicon), State of Bavaria, Fraunhofer-Gesellschaft, 29.03.2022

Dr. Henning Helmers, Dr. Oliver Höhn, Meike Schauerte
Best Paper Award, "Subcell Spectral Response Determination for Multi-Junction Photonic Power Converters based on Negative Bias-I-V Measueremen", OWPT Conference, 21.04.2022

Elisa Kaiser
Young Scientist Award, presentation, "Effects of Manufacturing Tolerances on Micro-CPV Module Performance", CPV-18 Conference, 25.04.2022

Franz Mantei, Dr. Ouda Salem
2nd Prize in the concept competition, "Fraunhofer 2030 klimaneutral", Project „Zero-Emission-Vehicle Concept Using FhISE n-COMET & CatVap® Technologies", Fraunhofer-Gesellschaft, 29.04.2022

Özde Seyma Kabakli
Best Poster Presentation Award, "Optimization of Serial Co-Sputtered Indium-Zinc Oxide (IZO) Films for Perovskite Silicon Tandem Solar Cells", 15th HOBV Conference, 19. – 25.05.2022

Arne Surmann
Best Poster Award, "Energiegemeinschaften in Österreich – lohnend auch für Deutschland? Eine Fallstudie im Projekt EnStadt:Pfaff" (Energy Communities in Austria – also Rewarding for Germany? A Case Study in the EnStadt:Pfaff Project), PV-Symposium, 23.06.2022

Johanna Kucknat
M.Sc. Prize of the Verein zur Förderung der solaren Energiesysteme e.V., M.Sc. thesis "The Role of the European Green Deal for the Decarbonization of the Chemical Sector", Verein zur Förderung der solaren Energiesysteme e.V., 12.07.2022

Dr. Juan Francisco Martinez Sanchez
1st Prize, Gips-Schüle Young Scientist Award 2022, Doctoral thesis "Development of Hybrid Concentrator/Flat-Plate Photovoltaic Technology to Reach the Highest Energy Yield", Gips-Schüle-Stiftung, 18.07.2022

Moderator Mai Thi Nguyen-Kim, Stefan Reichert (Fraunhofer ISE), Dr. Thorsten Ochs, Thomas Speidel (both from ADS-TEC Energy) and the German Federal President, Frank-Walter Steinmeier, during the prize-awarding ceremony for the "Deutscher Zukunftspreis" 2022.

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
1st Prize in the Science4Life Energy Cup in the business plan phase, Business plan "PV2plus", Science 4Life e.V., 18.07.2022

Stefan Reichert et al.
Nomination for the "Deutscher Zukunftspreis" 2022, Prize of the German Federal President for Technology and Innovation, Project "Elektroautos in wenigen Minuten aufladen – auch am leistungsbegrenzten Stromnetz ('ChargeBox')" (Charging Electric Cars in a Few Minutes – Even in a Limited-Power Electricity Grid), Geschäftsstelle Deutscher Zukunftspreis, Stifterverband für die Deutsche Wissenschaft, 06.09.2022

Natapon Wanapinit
Best Paper Award, "Electricity Trading in Local Sector-Coupled Energy Communities", 18th International Conference on the European Energy Market, 15.09.2022

Patrick Jürgens
Best Student Paper Award, "Modelling Germany's Energy Transition Within a 1.5 °C-CO_2-Budget", IAEE European Energy Conference, 24.09.2022

Clara Rittmann et al.
WCPEC Student Award, Paper "Epitaxially Grown p-type Silicon Wafers Ready for Cell Efficiencies Exceeding 25 %", WCPEC-8 2022, 26. – 30.09.2022

Philipp Kunze et al.
WCPEC Student Award, Paper "Contactless Inline IV-Measurement of Solar Cells Using an Empirical Model", WCPEC-8 2022, 26. – 30.09.2022

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
Make It Matter Award, "PV2plus", EWS Schönau and Smart Green Accelerator, 27.09.2022

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
1st Prize in "Pfiffikus" founders' idea prize, business idea "PV2plus", Bildungsstiftung Rhenania Freiburg e.V., 13.10.2022

Ai-Lin Chan
Robert-Mayr Young Scientists Award, M.Sc. thesis "Analysis of the Influence of Conditioning Procedures on PEM Electrolysis Cells via Impedance Spectroscopy", Eva Mayr-Stihl Stiftung, 19.10.2022

Pedro Viera Rodrigues
Robert-Mayr Young Scientists Award, M.Sc. thesis "The Doping Dependance of BH-Pair Formation and High and Elevated Temperature-Induced Degradation", Eva Mayr-Stihl Stiftung, 19.10.2022

Dr. Lukas Wagner
Eva-Mayr-Stihl Young Scientists Award, Doctoral thesis "Perovskite Photovoltaic Modules With a Very Low CO_2 Footprint: The in situ Technology", Eva Mayr-Stihl Stiftung, 19.10.2022

Clemens Dankwerth, Dr. Lena Schnabel
2nd Prize in Deutschen Rohstoffeffizienz-Preis, Project "LC150 – Entwicklung eines kältemittelreduzierten Wärmepumpenmoduls mit Propan" (LC150 – development of a reduced-refrigerant heat pump module with propane), German Federal Ministry for Economic Affairs and Climate Action (BMWK), 19.10.2022

Dr. Katharina Braig, Dr. Markus Glatthaar, Dr. Thibaud Hatt, Dr. Leonard Tutsch
1st Prize in CyberOne Hightech Award, Business Plan "PV2plus", bwcon GmbH, 10.11.2022

Chinmay Rayeev Bapat
M.Sc. Prize of the Verein zur Förderung der solaren Energiesysteme e.V., M.Sc. thesis "Development of Silicon Polymer Composites for Lithium Ion Batteries", Verein zur Förderung der solaren Energiesysteme e.V., 15.12.2022

Strategy and Business Areas

Our newsletters offer regular updates on our research highlights.

Contents

Focus on Technological Sovereignty and Sustainability

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

How has the omnipresent energy crisis of the past months affected the work of Fraunhofer ISE?
Henning: "It became even clearer that transforming the energy system is important, not only to reach our climate goals, but also to make our energy supply more independent and resilient. In addition, the market demand for almost all of the technologies which we address at the Institute has increased so massively that the market can hardly meet this demand."

Bett: "Our research and development is fundamentally orientated toward the long-term climate-protection goals. It is correct that an unprecedented demand for our clients' products has arisen, which they now want to and have to satisfy. In turn, we observe that we receive significantly more enquiries. Noticeable changes have also occurred in politics. One example is the call for energy sovereignty and more technological sovereignty. The Fraunhofer-Gesellschaft has been preaching this already for several years. For that reason, we are working on concepts to bring photovoltaic production back to Germany and to Europe."

How can more autonomy be achieved in European PV production?
Bett: "We must view the entire value chain. 97 % of wafers in the world come from China. That should change. We are well positioned in Germany to do that, because there is an innovation pipeline of good research results along the whole production process. However, potential investors still ask the question: What happens, if e.g. Chinese producers flood the market again with dumping prices? That is a question which must be solved politically with the right boundary conditions. Certainly, there is clear interest again in producing in Europe. To support the process, in 2022 we organized an investor workshop for the first time, on 'Technology meets Finance'. It was very successful and we will continue that in future."

Henning: "Research and development at the higher technological readiness levels, such as we conduct very successfully in PV-TEC, can also contribute to lowering the entry bars for investors. The Fraunhofer model of applied research, which is based on very close cooperation with manufacturers, is very well suited to achieving this objective."

Heat pumps as a key technology for the heat transition are currently a major topic. What contribution can Fraunhofer ISE make?
Henning: "It is now paying off that we have already been working on this topic for decades and were early advocates of the view that heat pumps will probably be the most important technology for the heat supply of the future. In this sector, there is also a well-positioned German and European industry. Nevertheless, the very rapid acceleration in demand is also accompanied by risks. Thus, the heating industry is well advised to embrace this transformation and industrialization of production wholeheartedly. Among other examples, the Institute very successfully completed a project recently, together with a broad industrial consortium, to develop a cooling circuit based on propane as an almost climate-neutral refrigerant. In a follow-up project, we now aim to cooperate with heat pump manufacturers and the housing sector to develop pilot solutions for heat pumps in apartment blocks, because currently there is not yet any adequate substitute for the gas-fueled single-story heating which is common there."

Which role will hydrogen play in the future energy system and how will Fraunhofer ISE develop this sector further?
Henning: "It is evident in all systems analyses that there will still be a need in future for fuels in applications where the use of electricity – including short-term storage with batteries – is

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

not possible at all or is very complicated. For example, aviation and shipping fall into this category. In addition, hydrogen will play a central role for the industrial transformation, such as in the chemical industry and steel production. The significance of research and development here will thus grow strongly. At Fraunhofer ISE, we have a wide R&D portfolio, from the production of hydrogen by electrolysis, through the utilization of hydrogen in fuel cells, to further conversion into many diverse molecules. In the enormous field of hydrogen technologies, there will be some developments which we cannot even foresee today."

In what other ways can Fraunhofer ISE contribute to acceleration of the transport transition?

Henning: "Electromobility will make an important contribution. One of the central questions there is how the necessary infrastructure will be designed so that vehicles can be charged quickly, in a grid-supportive mode. One development, which we have pursued together with our industrial partner, ADS-TEC, is the ChargeBox, a system in which a storage battery is combined with a charging unit such that vehicles can be charged quickly without the need for grid extension. This solution, in which we applied the most modern silicon carbide inverters, was nominated in 2022 for the 'Deutscher Zukunftspreis' (German Future Prize)."

Fraunhofer ISE has declared "Stationary Battery Storage" to be a key topic. What is the background?

Bett: "In Germany and Europe, significant activities in battery production were initiated in recent years, so that meanwhile there is a good number of producers with whom we can cooperate well in research and development. We have already achieved encouraging successes with the application of silicon as an anode material."

How can Fraunhofer ISE address battery research successfully?

Henning: "The topic is very important for us, which is why we have established extensive laboratory infrastructure for battery research in recent years. At present, we are successively taking more than 8500 m^2 of office and laboratory area into operation. In future, work will be done here on the entire spectrum of topics from novel battery cells, through processing technology and production questions, up to complete battery systems, including questions of quality assurance and lifetime. We are cooperating closely with the Fraunhofer Research Institution for Battery Cell Production FFB on upscaling questions. And we are working closely with further Institutes within the Fraunhofer Battery Alliance, for example on the topic of digital models."

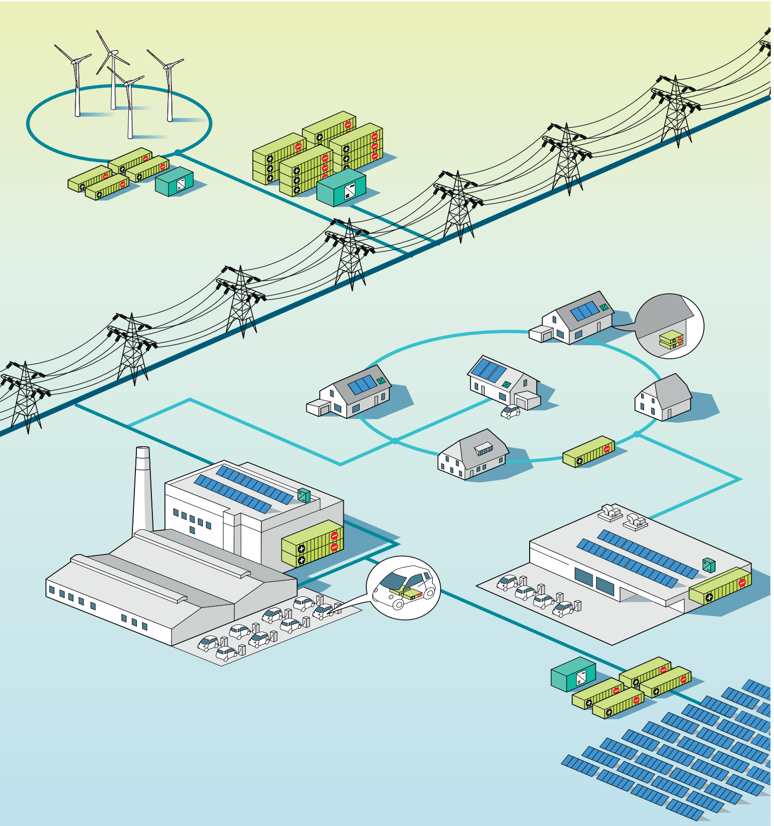
What is the status of technological sovereignty for batteries?

Bett: "In Germany and Europe, significant activities in battery production were initiated in recent years, so that meanwhile there is a good number of producers with whom we can cooperate well in research and development. We have already achieved encouraging successes with the application of silicon as an anode material."

How does Fraunhofer ISE treat the topic of raw material criticality in general?

Bett: "Circular value creation is anchored in our Institute strategy. This encompasses the second life of materials or components, through reuse of components, up to return of materials within closed cycles. It is also important to examine the availability of materials and complete value chains. For us, sustainability does not end with questions of resources, but also includes social aspects. We do not conduct our own research on this subject but can take these questions into account when analyzing production processes by cooperating with competent partners."

Stationary Battery Storage – Stability and Flexibility in the Energy System



Overview of various application possibilities for stationary battery storage.

The increasing share of renewably generated electricity and the associated complexity of future energy systems demand new approaches to ensure a stable and resilient energy supply. Stationary battery storage systems contribute essentially to meeting this demand: They support the grids, for example by providing balancing power, and can store excess power, ideally from photovoltaic or wind power plants, for an intermediate period and make it available on demand. One thing is clear: We need large amounts of stationary battery storage to achieve a safe and reliable power supply that is 100 % based on renewable energy sources.

At Fraunhofer ISE, we are addressing this thematic area with our key topic, "Stationary battery storage – stability and flexibility in the energy system". Our R&D activities range from battery materials and cell architectures, through battery technology and battery systems technology, up to questions on storage applications and research topics such as power electronics, energy management systems, grid integration and smart grids. Analysis of the storage requirements in the energy system is the basis for deciding on the main directions of our work. Scientific tests and assessments – both at the component and the system level – round off our offer.

Application Areas for Battery Storage

Home energy storage systems, consisting of smaller, decentralized storage batteries, have long been the state of the art in private houses and serve there as intermediate storage for PV electricity that has been generated on the house roof. District storage systems with larger capacities are used for intermediate storage in settlements and residential quarters, where they enable communal use of locally generated electricity.

Falling levelized costs of electricity from renewable sources and the general trend toward lower prices for batteries, on the one hand, and rapidly increasing energy costs and growing uncertainty in the established energy markets on the other, make commercial and industrial (C&I) storage systems increasingly interesting for applications in industry, the service sector and commerce. With their own generated electricity, businesses can become less dependent on volatile energy prices, guarantee a reliable power supply and can additionally contribute to reducing CO_2 emissions.

In a study on "Battery storage at former power station sites", we demonstrated that major expansion of large-scale battery storage systems offers enormous potential to meet the storage demand. Furthermore, large battery storage systems can be connected directly to PV power plants and thus ensure demand-responsive and yield-optimized electricity feed-in.

Advantages of stationary battery storage

The utilization of stationary battery storage enables large-scale integration of renewable energy and offers multiple advantages, regardless of the specific application area. Depending on the application-specific requirements, battery systems can be dimensioned from a few kilowatt-hours up to gigawatt-hours. The advantages encompass ecological, technical and economic aspects. In addition to positive effects on the environment, they increase public acceptance of the energy transition and open up new business opportunities for battery storage operators.

Bird's-eye perspective of the new Center for Electrical Energy Storage in the Haid industrial area of Freiburg.

Multi-functional battery storage: Intermediate storage of PV electricity to optimize self-consumption and to flatten load peaks.

Symposium at Fraunhofer ISE: "Can the Energy Transition Be Implemented Sustainably?"

Although basic research is so important, it alone is no longer enough. We must work on the problems, we must find solutions; to do that, we must think collaboratively and act on implementation. Interdisciplinarity and transdisciplinarity are essential for that and represent the first step together with society."

Prof. Daniela Kleinschmit
Deputy Vice-Chancellor, University of Freiburg

"Can the energy transition be implemented sustainably?" We at Fraunhofer ISE explored this question with lectures and a panel discussion on the occasion of the 60th birthday of Prof. Andreas Bett, a Director of Fraunhofer ISE. Representatives from natural and social sciences and business discussed how sustainability can be guaranteed en route to climate neutrality. The focus was on questions of resource consumption, the selection of suitable raw materials, environmentally benign production processes and possible approaches to achieve circular production methods. However, societal challenges and ethical questions accompanying progress toward a zero-CO_2 energy supply were also discussed intensely by the participants.

The starting point was the question as to what we actually understand "sustainability" to mean today – a concept which is in everyday use to an almost inflationary degree but is seldom questioned. Prof. Daniela Kleinschmit, Deputy Vice-Chancellor of the University of Freiburg, explained in her introductory lecture that the concept originated about 300 years ago in forestry. According to that concept, any tree that was felled in a forest had to be replaced by planting a new seedling – an approach that can hardly be reconciled with any economic model that is based on constant growth. Prof. Marc Oliver Bettzüge, an economist at the University of Cologne and a member of the Expert Council on Climate Questions to the German Federal Government, consequently reminded the listeners that also the manufacture, maintenance and disposal of PV power plants and wind parks can

be observed to simply continue in the tradition of extractive industrial processes. Nevertheless, as the discussion partners agreed in their first intermediate result, the establishment of a truly circular economy is an increasingly decisive factor for the future of humankind.

Fraunhofer ISE addresses this question from several different perspectives: In the economic political initiative on "Sustainable PV Manufacturing in Europe", we are aiming to achieve high-technology and sustainable PV production along the complete value chain. On the one hand, this would support independence from imports in the energy sector, a geostrategic goal. On the other hand, this would lead to creation of numerous jobs in the high-tech branch, a social aspect. Furthermore, we could thereby lay the foundation stone for a circular economy in the sense of sustainable production. Implicitly, this means that life cycle assessment (LCA), supply chain security and questions of manufacturing conditions are firmly anchored within research and practical implementation.

The topic of recycling also assumes a key role. Considering that materials such as lithium can be recycled only in very complicated processes, it becomes clear that research must increasingly work on new materials and technologies, meaning that the energy transition must also become a "material transformation", as Prof. Anke Weidenkaff postulated, the Director of the Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS.

Photos from left to right:

Institute Director, Prof. Andreas Bett, with his wife, Andrea Bett.

Panel discussion organized by Fraunhofer ISE (from left to right):
Prof. Anke Weidenkaff (Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS),
Prof. Daniela Kleinschmit (University of Freiburg),
Prof. Jan-Christoph Goldschmidt (University of Marburg),
Prof. Darrel Möllendorf (University of Frankfurt),
Bernward Janzing (moderator).

Institute Director, Prof. Hans-Martin Henning.

However, not only technological and economic questions need to be discussed: More than ever, science has the responsibility to transfer results into society and politics, as Prof. Jan-Christoph Goldschmidt from the University of Marburg emphasized. Prof. Darrel Möllendorf from the University of Frankfurt observed that the current debate revealed a conflict of interests between the duty to preserve the basis for life of future generations and the duty to combat poverty today in the global south. Against this background, it becomes clear that the acceptance – and thus the success – of the energy transition also depends essentially on our willingness to critically question our own habits and thought patterns.

Silicon Photovoltaics

"

With our research on fine-line metal-lization of solar cells, we aim to make photovoltaics yet more efficient, cost-effective and sustainable."

Katharina Gensowski M. Sc.
Researcher, Silicon Photovoltaics

Market Position

More than 95 % of all solar cells worldwide 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 in laboratories and technological centers occupying more than 3000 m², for example in our industrially relevant technological centers, PV-TEC and SiM-TEC and the Center for High Efficiency Solar Cells. The scientific and technological competence of our almost 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.

Leadership

Dr. Ralf Preu, Phone +49 761 4588-5260
Prof. Stefan Glunz, Phone +49 761 4588-5191

Facts and Figures

Total staff	289
Journal articles and contributions to books	56
Lectures and conference papers	50
First patent applications	6

Selected Projects in 2022

- Sustainable PV Manufacturing in Europe – An Initiative for a 10 GW GreenFab
- PrEsto – Perovskite Silicon Tandem Solar Cells: Development of Scalable Process Technologies
- NextTec – Promoting the Expansion of Photovoltaics by Cutting Production Times for High-Efficiency Solar Cells by Half
- PERC Solar Cells from 100 Percent Recycled Silicon
- Reassessment of the Intrinsic Bulk Recombination in Crystalline Silicon

More information on these and further projects

More information on this business area

III-V and Concentrator Photovoltaics

"

We achieve a record efficiency of 35.9 % with silicon-based III-V tandem cells. This means that we need much less area for solar modules."

Dr. Patrick Schygulla
Scientist, III-V and
Concentrator Photovoltaics

Market Position

In the area of III-V semiconductor solar cells, we are working on the most efficient PV technology and search for economically attractive solutions. Our III-V/Si tandem solar cells convert up to 35.9 % of solar radiation into electricity. For concentrated light, we are developing four-junction solar cells with an efficiency of up to 47.6 %. These are top international values for III-V photovoltaic technologies, which is distinguished by highest performance and long-term stability.

One focus of our research is to reduce costs with new production processes. In this way, we want to create attractive solutions in future for mass markets, e.g., for electromobility. Within concentrating photovoltaics, we develop micro CPV modules, in which new parallel production processes and self-orientation of miniaturized components are used. Our goal is economic solutions for high efficiency PV systems, e.g., for urban areas with limited space. In the III-V power by light sector, we enable new applications for telecommunication wave lengths, including sensors in passive optical networks.

Leadership

Dr. Frank Dimroth
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Facts and Figures

Total staff	46
Journal articles and contributions to books	15
Lectures and conference papers	18
First patent application	1

Selected Projects in 2022

- 50Prozent / 50Percent – Monolithic III-V Multi-Junction Solar Cells with More than 50 % Efficiency under Concentrated Irradiation
- H2Demo – Development of Demonstrators for Direct Solar Water Splitting
- QuintuMod – Development of a Low-Cost and Highly Efficient Solar Module Using a Solar Cell with 5-pn Junctions
- AIIR-Power – AI-assisted Design and Fabrication of Photonic Infrared Power Converters for Energy and Telecommunications
- Hiperion – Hybrid Photovoltaics for Efficiency Record Using Integrated Optical Technology

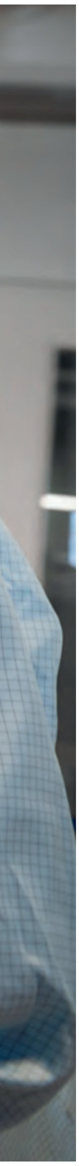
More information on these and further projects

More information on this business area

Perovskite and Organic Photovoltaics

"The use of transparent solar cells in windows and polymer films offers exciting options to the building sector and agriculture for a successful and affordable energy transition."

Dmitry Bogachuk
Scientist, Perovskite and Organic Photovoltaics Department



Market Position

The efficiency of perovskite solar cells can be further increased, particularly by tandem solar cells consisting of two different perovskite absorbers. The goal of Fraunhofer ISE is to realize this potential while taking the factors of upscalability, long-term stability and production costs into account. In parallel, we also investigate the combination of perovskites and silicon for highly efficient tandem cells.

In organic photovoltaics, we are working intensively on using the unique optical properties of organic semiconductors. They can absorb strongly in the near infrared spectral range, while simultaneously exhibiting high transparency in the visible spectral range. In contrast to modules with opaque cells, in which a degree of transparency is achieved by gaps between the cells, the aesthetically attractive homogeneous appearance opens up new large-area application potentials – particularly in buildings and agriculture. The simple integration of organic photovoltaics benefits such applications.

Leadership

Dr. Uli Würfel
Phone +49 761 203-4796

Facts and Figures

Total staff	37
Journal articles and contributions to books	23
Lectures and conference papers	19

Selected Projects in 2022

- ADAPT – Climate Adaptation through Organic Agri-Photovoltaics
- See-Through-PV – Development of Organic Solar Modules with High Visual Transparency
- PeroTec Efficiency Phase 1 – Development of Process Technology for Highly Efficient Long-Term Stable Perovskite Solar Cells Based on the PeroTec™ Approach
- SuPerTandem – Ultra-Stable, Highly Efficient, Low-Cost Perovskite Photovoltaics with Minimized Environmental Impact
- DIAMOND – Perovskite Photovoltaics with Minimized Ecological Footprint

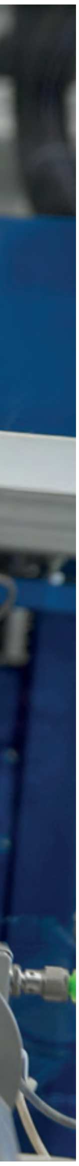
More information on these and further projects

More information on this business area

Photovoltaic Modules and Power Plants

"We strengthen the position of our industrial partners in the market by our research on innovative, resource-conserving module technologies such as conductive adhesives."

Torsten Rößler
Group Leader, Photovoltaic Modules and Power Plants



Market Position

With the renewable energy law (EEG) of 2023, a German Federal government has defined, for the first time, long-term and ambitious goals for PV installation that support the energy transition. The resulting planning certainty helps all actors in the PV sector. For example, it is clear that the production capacity in Germany and Europe must be massively increased to achieve annual increases of up to 22 GW_p installed PV power. We support our partners from mechanical engineering and module production in achieving high efficiency with technological developments such as conductive adhesives and matrix-shingle cell connections.

For the rapidly growing PV power plant park, we develop accurate tools for quality assurance of modules and plants, as well as digital operation management and power forecasting. Photovoltaics requires large areas – our approaches to integration and dual use of surface areas are accompanied by optimized module designs, mounting structures, potential analyses and reliability testing. Synergistic effects result which also benefit agriculture, water-body ecology, buildings and vehicles.

Leadership

Dr. Harry Wirth
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Facts and Figures

Total staff	217
Journal articles and contributions to books	17
Lectures and conference papers	51
First patent applications	6

Selected Projects in 2022

- GEPARD – High-Throughput Production System and Process Technology for Crystalline Silicon Solar Modules
- CTS1000+ – More Energy per Cell Power – Holistic Cell-to-System Module Yield Increase
- APV Obstbau (Orcharding) – Agrivoltaics as Resilience Concept for Adaptation to Climate Change in Orcharding
- APV-MaGa – Agrivoltaics for Mali and Gambia: Sustainable Electricity Production by Integrated Food, Energy and Water Systems
- PVwins – Development of Wall-Integrated PV Elements for Noise Protection
- Lade-PV – Development of Vehicle-Integrated Photovoltaics for On-Board Charging of Electric Utility Vehicles
- PV2Go – Solar Potentials of German Traffic Routes

More information on these and further projects

More information on this business area

Energy Efficient Buildings

> **"We are convinced that we should concentrate on using ambient heat and green electricity for the heating supply of the future."**

Theresa Paul
Scientist, Heating and Cooling Technology

Market Position

The dramatic circumstances accompanying the war in the Ukraine have a major effect on the heating market due to the shortage of natural gas, the dominating fuel for providing heat. Accelerated transition to renewable sources of energy has become more urgent, not only for climate-protection reasons but also because of the supply security aspect.

The challenge is to provide solution approaches which address a large spectrum of actors: technologies for fossil-free heat generation, transformation concepts for the housing market, industry and heating suppliers, as well as the digitalization of trades and planning processes.

Productivity in the building sector, particularly in the plumbing and heating trades, can be achieved by digitalization of the processes. We are currently working on automated documentation of existing installations and preparation of quotes. To ensure that the accelerated expansion of heat pump installations can succeed with natural refrigerants, we are providing technological support to the development of optimized refrigerant circuits.

Leadership

Dr. Peter Schossig
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Facts and Figures

Total staff	132
Journal articles and contributions to books	17
Lectures and conference papers	25
First patent applications	2

Selected Projects in 2022

- KETEC – Research Platform Refrigeration and Energy Technology
- FernWP – District and Process Heating by Heat Pumps Instead of Coal Combustion
- BIPV Initiative Baden-Württemberg (Building-Integrated Photovoltaics)
- Artificial Intelligence for Heat Pumps
- LC150 – Development of a Refrigerant-reduced Heat Pump Module with Propane

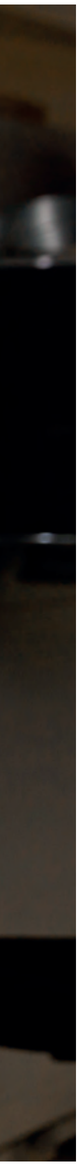
More information on these and further projects

More information on this business area

Solar Thermal Power Plants and Industrial Processes

"Heat pumps for high temperatures and power have the potential to decarbonize the industrial heat demand."

Hannah Teles de Oliveira
Doctoral candidate, Solar Thermal Power Plants and Industrial Processes



Market Position

Current developments in the energy market pose major challenges to households and German industry. At the same time, renewable solutions are becoming economically more attractive. In addition to short amortization periods, they offer a large degree of independence from future developments, reliable cost planning and, in combination with storage, high security of supply. Together with efficiency measures and the use of waste heat, a significant contribution can be made to the heat transition in industry, particularly by hybrid concepts which combine the advantages of different technologies. Technically mature solutions for renewably generated heat already exist today for temperatures of up to about 250 °C, e.g., to supply industrial steam networks. We support industry on its path toward climate neutrality with research on solar thermal energy applications, high-temperature heat pumps and thermal storage, so that industrial companies can continue to succeed within the competitive global market.

Another central topic of our research is resource efficiency. In this context, we develop e.g., membrane-based processes to recover valuable materials from industrial wastewater and to extract useful raw materials from natural brines.

Leadership

Dr. Peter Nitz
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Facts and Figures

Total staff	65
Journal articles and contributions to books	7
Lectures and conference papers	11

Selected Projects in 2022

- AVUSpro – Automated In-Situ Measurement of Soiling for Site Assessment and Operation of Solar Thermal Power Plants
- Polyphem – Small-Scale Solar Thermal Combined Cycle (Gas Turbine/ORC)
- SOLBEADO – Development and Testing of Secondary Reflectors for a Beam-Down Tower Power Plant
- SmartCSP – Application of AI Methods to Improve Operations and Maintenance in CSP Power Plants
- FENOPTHES – Development and Optimization of Filler Materials for Thermal Storage
- Optimus – Development, Optimization and Application of PCM Emulsions with High Thermal Storage Density
- SEArcularMINE – Extracting Raw Materials from Concentrated Sea Water

More information on these and further projects

More information on this business area

Power Electronics, Grids and Smart Systems

> **"Intelligent integration of distributed resources into the energy system is mandatory for a successful energy and heat transition."**

Jasmin Montalbano
Scientist, Grid Operation and Grid Planning

Market Position

In the business area for "Power Electronics, Grids and Intelligent Systems", we address innovative technologies to transform the electricity system. This requires detailed analysis of the current electricity system; we contribute to its public transparency with our online evaluation tool, "Energy Charts". In our current study on the levelized cost of electricity, we determine the costs of available generation technologies and conduct research on the cost degression trend. This information forms the basis for transformation scenarios, which we develop with our REMod simulation tool. The present REMod study demonstrates how we can achieve a zero-emission energy system in a cost-optimized way that finds widespread social acceptance.

Due to increasing inter-sectoral coupling, the electricity grid is becoming the hub for integration of renewably generated energy. The associated demand for digitalization is met with the help of power electronics and smart grid technologies.

Leadership

Prof. Christof Wittwer
Phone +49 761 4588-5115

Facts and Figures

Total staff	142
Journal articles and contributions to books	17
Lectures and conference papers	35

Selected Projects in 2022

- MS-LeiKra – Power Electronics for the Next Generation of Medium Voltage PV Power Plants
- Power4re – Reliable Power Converter for the Provision of Renewable Energy
- VerbundnetzStabil – Stable Power System Behavior with Converter-based Generation
- EnStadt:Pfaff – Decentralized Energy Management from the Smart Home to the Urban Quarter
- IND-E – Decarbonization and Electrification Potentials of the German Industry
- TransDE – Transformation of the German Infrastructure by 2050 in Harmony with the Energy Transformation of all Consumption Sectors
- InteRessE – Resource Demand for the Energy Transformation

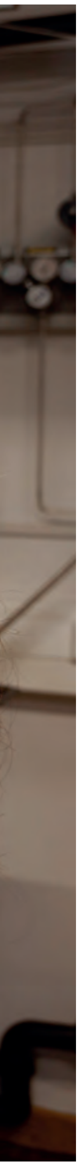
More information on these and further projects

More information on this business area

Hydrogen Technologies

"We investigate the interaction between material properties, microstructures, production processes and the operating behavior of fuel cells."

Neethu Thombra
Staff member,
Fuel Cell Systems



Market Position

Being a sustainable fuel, hydrogen offers a huge potential for the global energy system transition towards net-zero emissions. Produced with "green" electricity, it plays a key role in establishing climate-neutral industrial processes and sustainable mobility as well as flexible electricity generation. As a result, the global market development of hydrogen applications is extremely dynamic.

We accompany these processes with the development of efficient technologies along the entire value chain and transform them into applications with our range of services. In addition, we conduct life cycle assessments to determine the greenhouse gas potential of various processes and calculate the costs of hydrogen products by techno-economic analysis. As a research service provider, we contribute to the successful realization of the global energy transition by the development of a sustainable, international hydrogen economy.

Leadership

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Facts and Figures

Total staff	133
Journal articles and contributions to books	10
Lectures and conference papers	17
First patent applications	2

Selected Projects in 2022

- CINES – Fraunhofer Cluster of Excellence Integrated Energy Systems CINES
- H2Carsharing – Testing of FCEV in Car Sharing
- Carbon2Chem® Phase 2
- FC-CAT – Fuel Cell CFD and Through-Plane Modeling
- FC-RAT – Realistic Aging Trend Modeling of Fuel Cells

More information on these and further projects

More information on this business area

Electrical Energy Storage

"Battery safety is an important precondition for success in the energy and transport transition. Our research is devoted to improving it continuously."

Dr. Nina Kevlishvili
Project leader, Battery Systems Technology

Market Position

The technological requirements on batteries are increasing continually: The approaching transport transition, energy supply systems with a large share of renewably generated electricity and a massive increase in portable devices are all significant contributing factors. In particular, the development of a sustainable transport sector with its diverse market segments – lightweight electric vehicles, electric cars, electric and hybrid heavy-duty vehicles and the electrification of aviation and shipping – demands technical innovations.

At our new "Haidhaus" site, with a laboratory floor area of around 5 500 m², we are developing highly efficient, safe and reliable batteries for all of these applications. Our research extends along the entire value chain – from materials and cells, through battery systems engineering, to diverse applications of battery storage units. Furthermore, we offer a wide range of testing and assessment. In view of the globally growing demand for lithium-ion batteries and dependence on raw materials, we consider the establishment of a sustainable circular economy to be just as important as research on alternative technologies, e.g., the zinc-ion batteries which we helped to develop.

Leadership

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

Facts and Figures

Total staff	70
Journal articles and contributions to books	3
Lectures and conference papers	16

Selected Projects in 2022

- SICOM-LIB – Silicon Composite Anode Materials for Lithium Ion Batteries
- ecoLEPuS – Second Life Batteries for Use in High-Performance Applications Using the Example of Buffer Storage in Charging Infrastructure
- PIONEER – Airport Sustainability Second Life Battery Storage
- SIMBA – Sodium-Ion and Sodium Metal Batteries for Efficient and Sustainable Next-Generation Energy Storage
- FLiBatt – Solid Lithium Batteries with Non-Woven Materials
- EMILAS –Electromobility in Apartment Buildings with Intelligent Charging Stations and Second-Life Batteries
- ResHy – Resource-Saving Hybrid Battery - Construction, Integration and Operational Optimization

More information on these and further projects

More information on this business area

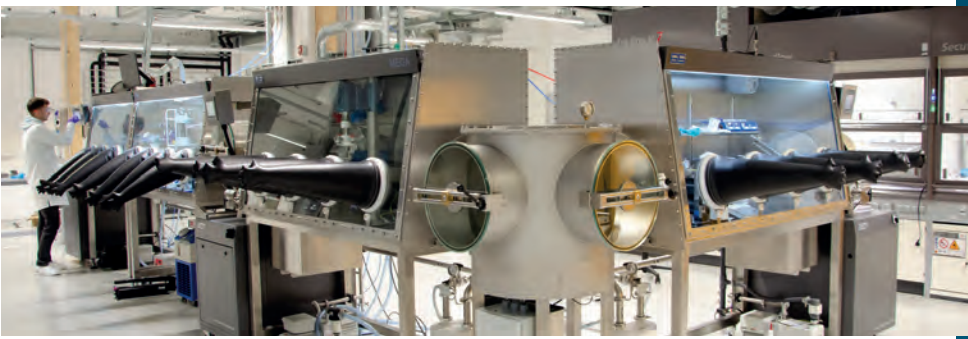
The new Center for Electrical Energy Storage

Personnel air lock for changing into and out of personal protective clothing (above); Processing of powders, mixing of electrode slurries and products of novel, silicon-based active materials (center); Cycling of lithium-ion test cells in a cell tester (below).

For a number of years, Fraunhofer ISE has been working on implementing an R&D strategy for batteries along the entire value chain. After several years of planning and building, the goal was finally reached: At the beginning of 2022, the first working group moved to our new site in the south of Freiburg, into the "Haidhaus", as our new "Center for Electrical Energy Storage" is now called internally and publicly. Located under the single roof of the new building, in future we will conduct research on innovative battery materials and cells, work on optimized solutions for battery systems and their integration into very diverse applications, and carry out extensive scientific tests and assessments of cells, modules and systems within the framework of quality assurance.

The focus of our work at the materials and cell level is the exploitation of the still large potential for optimization in the field of lithium-ion technology. This applies, for example, to the application of silicon-based anode materials or cathode materials with higher specific capacity, as well as research on different approaches relating to solid-state batteries. Particularly for stationary applications, there is a whole range of alternative innovative technologies, some of which are still at a low Technology Readiness Level (TRL), but others which are shortly before market introduction. This includes the zinc-ion battery which we helped to develop, as an example.

At the system level, we address central questions relating to the development of safe, reliable and high-performance battery storage units. This includes the packaging and circuit integration technology, thermal management and the application of propagation-hindering materials, as well as efficient battery management systems with precise algorithms to determine the state of charge and to predict the lifetime.



Processing sequence to produce battery cells with a solid-state electrolyte, from powder to the cell within a glovebox line.

As aging is particularly significant in this context, we investigate the aging mechanisms and the influence of different application-specific conditions and operating modes, both in the laboratory and with the help of simulation models. In addition to the widespread lithium-ion batteries, we are also conducting research in our projects on alternatives such as sodium-ion batteries, e.g., within the EU-funded "Simba" project.

Nowadays, batteries are used in numerous applications with very different specifications. Thus, we address the selection of technology, simulation-based system design and the development of optimized strategies for storage operation management in our work on system integration and storage applications. Furthermore, we work in our new laboratories on establishing systemic solutions, accompany field projects and offer scientific monitoring as well as the analysis of operating data in the context of holistic quality assurance.

The rapid technological development in the field of conventional and innovative batteries leads to an ongoing demand for comprehensive tests and assessments. To meet this demand, we have extended our laboratory infrastructure appreciably at the new location. Thus, we are now able to subject significantly larger numbers of battery cells, modules and systems to performance and aging tests and also to develop quality assurance methods for cell production and extension of the service life. Furthermore, in our new premises, we can investigate the safety of batteries according to both common standards and clients' specifications.

Contact

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"Batteries are a key component for the success of the energy and transport transition.

Fraunhofer ISE works on application-oriented solutions along the entire value chain."

Dr. Nicole Hoffmeister-Kraut
Minister for Economic Affairs, Labor and Tourism of Baden-Württemberg, Germany

R&D Infrastructure

A special feature of Fraunhofer ISE is its excellent technical infrastructure. Laboratories with a floor area of 20 900 m² – including 1 070 m² of clean-room area – and extremely modern equipment and facilities are the basis for our competence in research and development. Our goal is to find promising technological solutions and transfer these into the economy and society. Our industrial partners profit from the know-how of our staff as well as the continuous expansion of our technical infrastructure. Particularly small and medium-sized enterprises without their own R&D departments gain access to high-performance laboratory infrastructure and excellent research achievements by cooperating with Fraunhofer ISE.

In 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 50 ff.).

In our eight laboratory centers and four production-relevant technological evaluation centers, we develop new products, processes and services and optimize existing ones. Last year, we commenced our activities in the new Center for Electrical Energy Storage (pages 46/47).

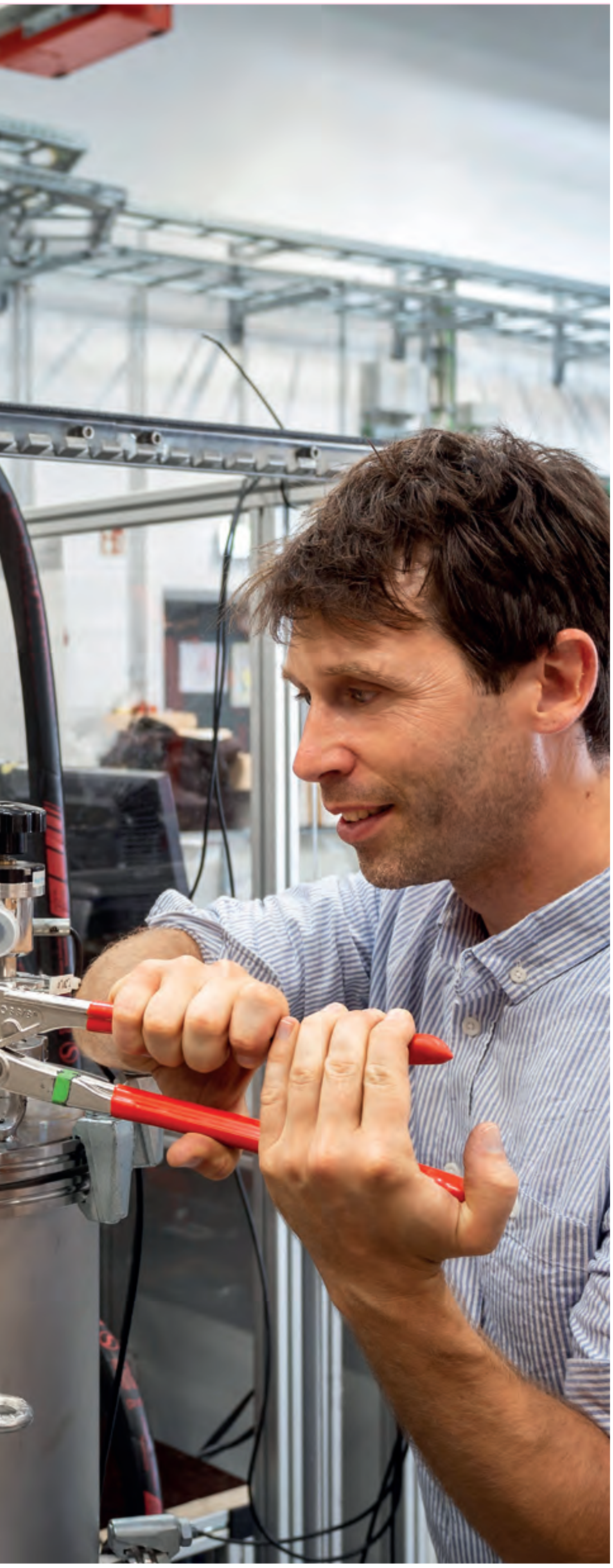
Technological Evaluation Centers

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

Test rig for the characterization of adsorption heat pumps.

Accredited Laboratories

CalLab
PV Cells

Calibration of Solar Cells

Silicon, Thin-Film, Perovskite, Organic Solar Cells
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Wendy Schneider
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Multi-Junction and Concentrator Cells
Dr. Gerald Siefer
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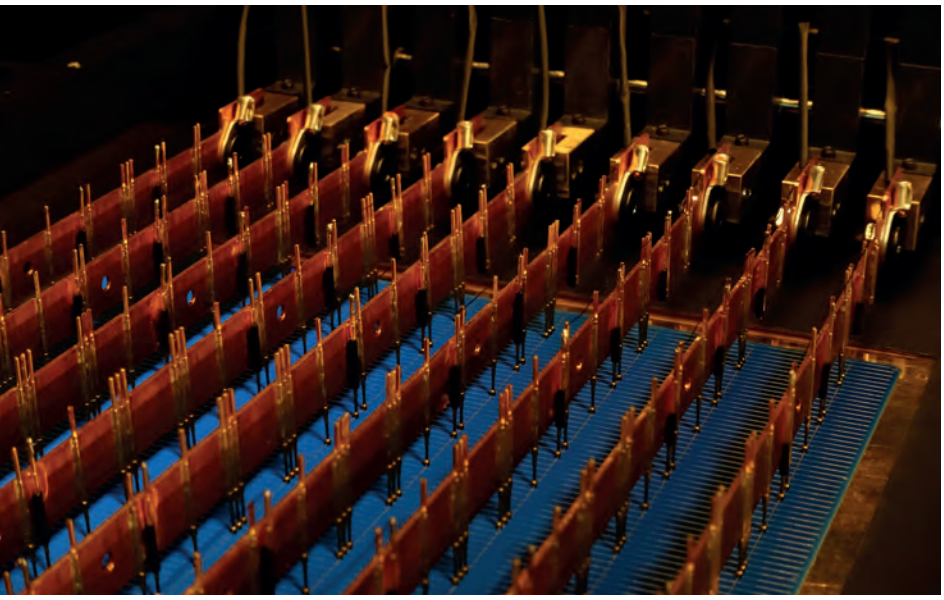
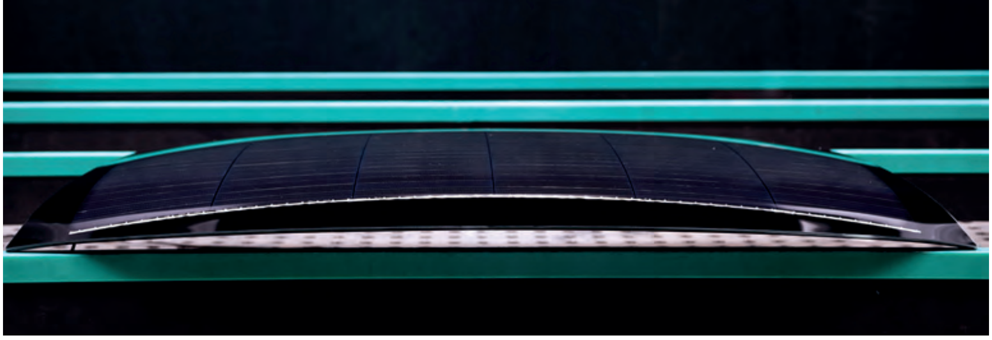
In CalLab PV Cells, we offer the calibration of solar cells representing a wide range of PV technology. The laboratory is accredited for solar cell calibration with the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body) and counts as one of the internationally leading photovoltaic calibration 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 illumination of either both surfaces or only a single surface. Our clients profit from the further development of our existing test rigs, which offer very high accuracy and short measurement times. Furthermore, we make measurements of multi-junction solar cells with various multiple-source simulators 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.



Measurement of a multi-busbar cell.



Preconditioning of a VIPV module before a power measurement.

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 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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TestLab
PV Modules

Quality Assurance of PV Modules

TestLab PV Modules tests the quality and reliability of PV modules. Our accredited laboratory is equipped with modern and innovative testing facilities that can be used for applications that extend well beyond standard testing procedures.

We advise our clients on cost-effective and time-efficient testing programs and 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 generate more power, 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 prominent role here. The application areas are also constantly being developed further: Building or vehicle integration demands new boundary conditions for module testing. Often, the specifications in existing standards are not clear concerning the testing of such modules. We thus investigate the applicability of testing and measurement procedures for these technologies 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.

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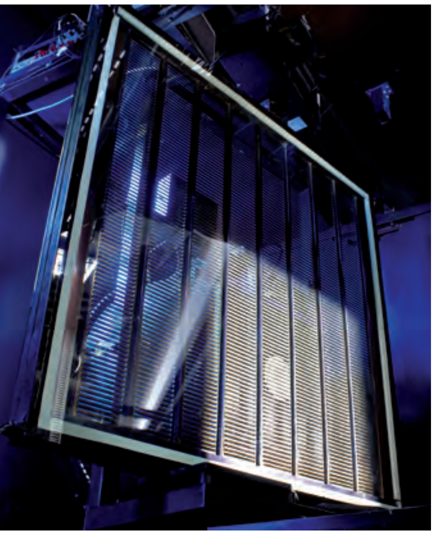
The reliability, quality and safety of PV modules are tested for certification.

Transmittance measurement of a partly transparent façade collector in TestLab Solar Façades.



Shear load test of a complete system consisting of two collectors with a mounting system, including connection to the load-bearing structure up to the roof rafters.

TestLab
Solar Façades

Characterization of Façades and Building Components

In TestLab Solar Façades, we characterize transparent, translucent and opaque materials, test building envelope components and evaluate the energy-relevant, thermal and optical properties of complete façades. This encompasses both "passive" façade components 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 authorization and certification of solar thermal collectors and thermal storage units, as well as complete systems and their components for heating, ventilation 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 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, we 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 program.

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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 (with heat, natural gas or test gas) can also be measured. The laboratory is equipped with an integrated safety concept which allows components and systems with flammable refrigerants or ammonia to be 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 m^3/h to 5000 m^3/h) can be conditioned in the temperature range from -15 °C to +50 °C and relative air humidity from 15 % to 95 %.

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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Calibration of measurement equipment for air temperature and humidity in the calorimetric climatic chamber.

Characterization of Power Electronic Equipment

The accredited TestLab Power Electronics offers testing of electric units and systems in the high-power range up to 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 laboratory equipment enables us to test the electric properties of inverter systems, characterize them according to grid codes 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 spatially distributed and synchronized as required in the field.

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

TestLab
Power Electronics

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Multi-Megawatt Lab at the Center for Power Electronics and Sustainable Grids.

Highlights of Our Research

"

Realizing sustainability in all aspects of our R&D is one of our most important goals."

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

Contents

Topics which have a strong influence on our work in the context of the energy transition and sustainability are identified with this symbol.

Highly Efficient and Stable Perovskite Solar Cells with Graphite Electrodes

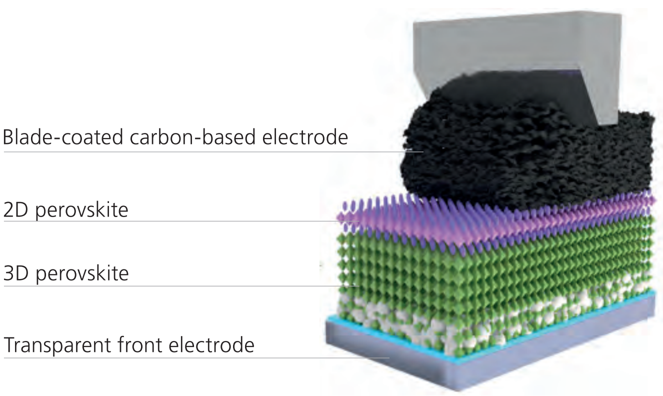

Illustration of perovskite solar cells with blade-coated carbon-based electrodes featuring a 2D perovskite-based electron-blocking layer.

Although perovskite photovoltaics appears to be close to commercialization, its comparatively low long-term stability has prevented it from becoming established on the PV market up to now. Part of the stability problem can be attributed to the metal-based back electrodes, which irreversibly degrade the solar cell under different stress conditions (e.g., light, temperature, moisture) and cause a loss in performance. To avoid this problem, chemically inert and hydrophobic electrodes based on graphite can be used, which extend the lifetime of the component. However, the performance of solar cells with graphite electrodes is generally poorer than that of standard cells with metal electrodes. This is mainly due to the lower conductivity of the carbon-based materials and poorer contact to the underlying layers, which cause additional power losses.

Fraunhofer ISE succeeded in demonstrating that these cells typically suffer higher recombination losses at the interface between the graphite electrode and the perovskite. To solve this problem, we cooperated with the École Polytechnique Fédérale de Lausanne (EPFL) to develop a two-dimensional material based on perovskite, which functions as an electron barrier layer and effectively suppresses the unwanted diffusion of electrons to the graphite electrode. At the same time, a favorable position of the energy bands enables efficient extraction of holes, which leads to excellent opto-electronic properties and a solar cell efficiency of 18.5 %. Furthermore, the carbon-based electrodes were deposited by blade-coating, a technology which can be upscaled and is thus suitable for producing not only solar cells on a laboratory scale but also large-area PV modules. The unique combination of high efficiency, long-term stability and upscaling potential shows that perovskite solar cells and modules with graphite electrodes have the potential to make a sustainable contribution to the next generation of PV technology. These promising results were recently published in the renowned scientific journal, "Advanced Energy Materials". They were obtained within the European research project, "UNIQUE", which addresses the development of stable, efficient and upscalable perovskite PV with graphite electrodes.

The researchers at Fraunhofer ISE are cooperating actively with industrial partners throughout Europe to produce stable and efficient, large-area perovskite solar modules. As has already been demonstrated, these modules can pass demanding stability tests, underlining the excellent prospects for these components with regard to sustainable and long-term electricity generation.

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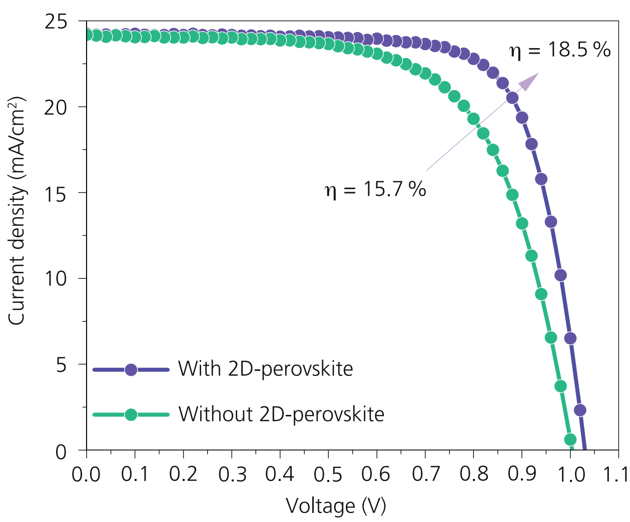
Current density versus voltage for solar cells with and without a 2D perovskite layer, showing a large difference in power conversion efficiency (η) .



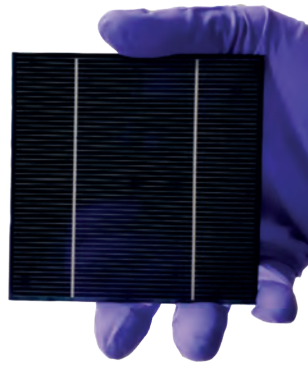
Large-Area Perovskite-Silicon Tandem Solar Cells

Perovskite-silicon tandem solar cells represent a further development of the established standard technology based on silicon wafers. A perovskite solar cell with a large band gap is produced on a silicon solar cell so that better use is made of incident solar radiation. For laboratory-scale cells, the currently published efficiency is 31.3 %, which already indicates the potential of this technology. However, the surface area of the laboratory cells is still small (app. 1 cm^2) and not all of the methods that have been tried out in the laboratory can be scaled up for industrial manufacturing.

In addition to continual further materials development of the tandem systems on small areas, Fraunhofer ISE is also developing technology for industrial mass production. The "PrEsto" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), focuses on the so-called hybrid process. In the first step, we evaporate the inorganic components onto the bottom solar cell. In the subsequent step, we deposit organic salts by spraying, inkjet printing or using slot dies. The advantage of this approach is that it allows also textured silicon solar cells to be coated conformally. The pyramidically structured surface is not only the standard for industrially manufactured solar cells but also has a positive effect on the achievable efficiency and the annual energy yield which can be expected in field applications.

In the PrEsto project, we evaluate different production processes for perovskite top solar cells. These are suited for large-area coating of the silicon bottom solar cells that are already manufactured industrially and can be scaled up for mass production. We cooperate with our partners to investigate materials adaptations to the tandem systems and technical boundary conditions during production.

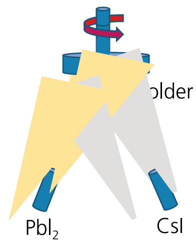
The Fraunhofer flagship project, "MaNiTU", is accompanying these research and development activities. The focus here is on high efficiency and the development of sustainable materials for perovskite-silicon tandem solar cell applications. With classic spin coating processes on planar surfaces, we have already achieved peak efficiency values of 26.8 % on small areas (0.25 cm^2) and 22.5 % on a large area (104 cm^2) and certified them in CalLab PV Cells. The most recent tandem results of 28 % (0.25 cm^2) were obtained by optimizing the front contact. They represent an important milestone along the route to tandem efficiencies of 30 % and higher.

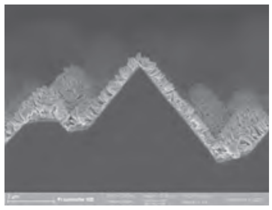


104 cm^2 large-area perovskite-silicon tandem solar cell with screen-printed front metallization and a certified efficiency of 22.5 %.

Step 1

Thermal evaporation of PbI_2 and CsI.





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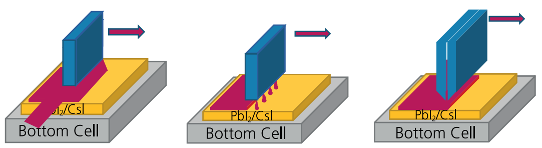
Step 2

Infiltration with organic salt solution via spray coating, inkjet printing or slot die-coating (or spin coating for reference).



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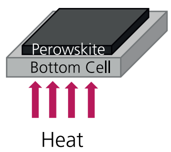

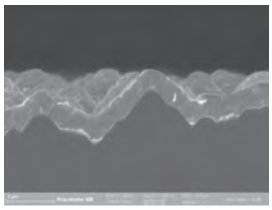

By applying the two-step hybrid route, even textured silicon bottom solar cells can be conformally coated by a perovskite top solar cell.

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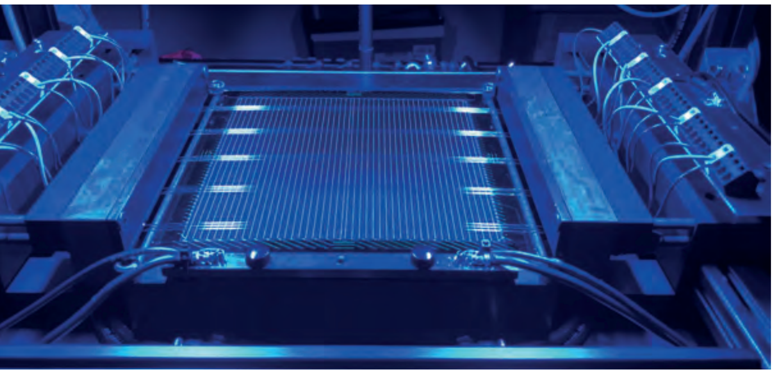
Calibration of Perovskite-Silicon Tandem Solar Cells and Modules



Homogeneous bias illumination (here blue for the perovskite top cell) allows precise determination of the global quantum efficiency of the sub-cells.

Perovskite-silicon tandem solar cells are showing a remarkable development toward higher efficiencies, improved stability properties and industrially applicable processes. To ensure that this technology can become established on a widespread technological basis in future, independent and reliable, certified determination of the efficiency is needed to enable objective comparisons between different processing routes and to evaluate them economically.

Due to the direct production of a monolithic tandem composite, the two sub-cells are no longer individually accessible without taking further measures. Because small differences in the quantum efficiencies of the sub-cells due to an incorrectly selected spectral distribution of the measurement radiation can already lead to significant deviations in the cell parameters, it is mandatory to use spectrally adjustable excitation radiation. In contrast to measurements of III-V-based tandem cells, account must be taken of larger cell areas and specific meta-stable states, which means that excitation under continuous radiation and adapted measurement routines are needed.

Within the "KATANA" research project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is working on methods to calibrate the cell and module parameters of this new type of solar cell under continuous radiation with accurately tunable excitation spectra. Fraunhofer CalLab PV Cells developed suitable procedures for calibrated measurement of the global quantum efficiency (left-hand figure) and the current-voltage parameters. Applying them, we measured calibrated record efficiencies for 6" tandem cells and reported the results in the "Solar Cell Efficiency Tables". Further-reaching spectral metric analyses provide detailed insight into current limitations of the sub-cells and enable improved understanding for cell development.

We are working continually to reduce our measurement uncertainty still further and to develop appropriate calibration procedures for tandem modules in CalLab PV Modules, that are based on the measurement procedures for tandem solar cells. An additional challenge here is to monitor the homogeneity of the continuous excitation spectrum over the large, irradiated area, which can be implemented e.g., by high-power LED arrays with a large number of different wavelengths. To cope with meta-stable behavior, we develop preconditioning procedures to bring the module into a reproducible state for the measurement. The long measurement times under continuous irradiation demand precise thermal control of the module temperature to minimize additional contributions to measurement uncertainty. In making the measurements, it is very important to take monofacial and bifacial cell architecture into account.

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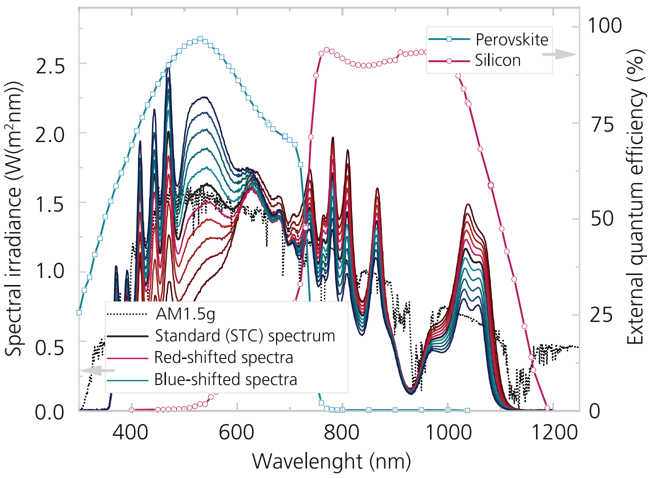
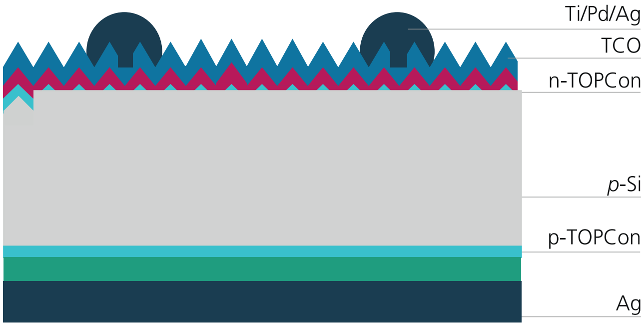


Variation of irradiance spectra for spectrometric characterization of a tandem solar cell represented by the quantum efficiency of the top (blue) and bottom (red) cells.

TOPCon Structures for Application in Perovskite-Silicon Tandem Solar Cells

Crystalline silicon solar cells have dominated the global photovoltaic market for decades. Evolutionary further developments have led to an annual increase in the efficiency of app. 0.5 $\%_{abs}$. However, recombination losses at the metal-semiconductor interfaces limit the performance of industrially dominating PERC technology. The TOPCon (Tunnel Oxide Passivated Contact) technology developed at Fraunhofer ISE, which is now widespread, addresses this issue with passivating contacts that are selective to charge carriers. The generation of electron-hole pairs in the silicon absorber and their separation at the electrodes are thereby spatially separated from each other. With this advanced technology, we achieved a record efficiency of 26.0 % for p-type solar cells.

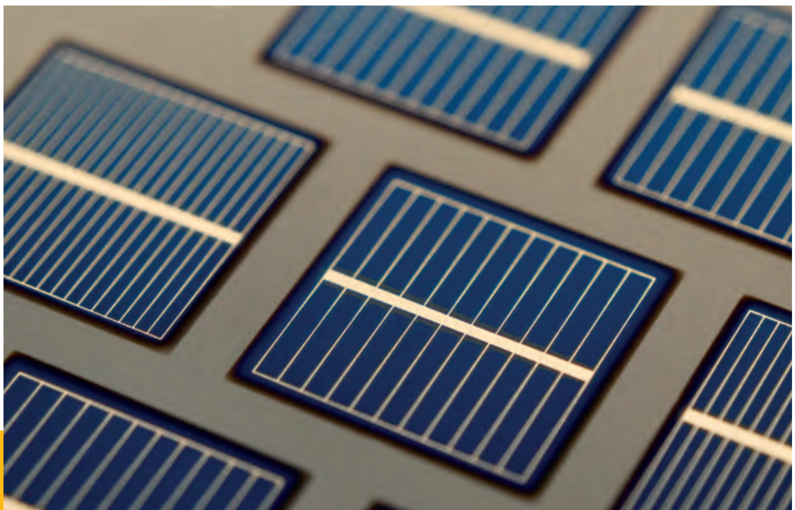


Structure of the p-type solar cell with n-TOPCon on the front and p-TOPCon on the back.

However, every solar cell material has a clear physical limit to its efficiency, which has a value of 29.4 % for silicon (Si). The potential efficiency can be increased significantly by the application of tandem solar cells, for example with a silicon bottom cell and a perovskite top cell. Passivating contacts based on polycrystalline Si are also a focus of Fraunhofer ISE in developing a high-efficiency and cost-effective silicon bottom cell. In particular, we anticipate very high potential efficiency and high economic viability from the $TOPCon^2$ cell with full-area TOPCon front and back contacts. Whereas the n-doped TOPCon contact achieved excellent passivation on planar and textured surfaces (J_0 = 1 fA/cm^2), the predicted potential could not yet be exploited completely for the p-doped TOPCon contact.

Thus, comprehensive work is being done at Fraunhofer ISE to gain fundamental understanding of the function and the limitations of this contact. We were able to demonstrate that the interplay between the stoichiometry of the extremely thin interfacial oxide and the high-temperature annealing step as well as an effective hydrogen passivation play a decisive role. Based on these investigations, the passivation of the p-doped TOPCon contact has now been improved decisively. Saturation current densities J_0 of 7 fA/cm^2 were achieved on planar surfaces and 17 fA/cm^2 on textured ones. At the same time, we obtained very good contact properties with a contact resistance of ρ_c = 5 $m\Omega\ cm^2$. We have integrated the n-doped and p-doped TOPCon contacts into $TOPCon^2$ solar cells to test their suitability for application as bottom cells, whereby the open-circuit voltages (V_{oc}) and the filling factors (FF) are the essential parameters for evaluation. The $TOPCon^2$ solar cells show very good V_{oc} values of up to almost 720 mV and FF up to 81 %. With these values, this cell is a very promising candidate for a bottom cell in a monolithic perovskite-silicon tandem solar cell.

Front surface of 2x2 cm^2 TOPCon solar cells.



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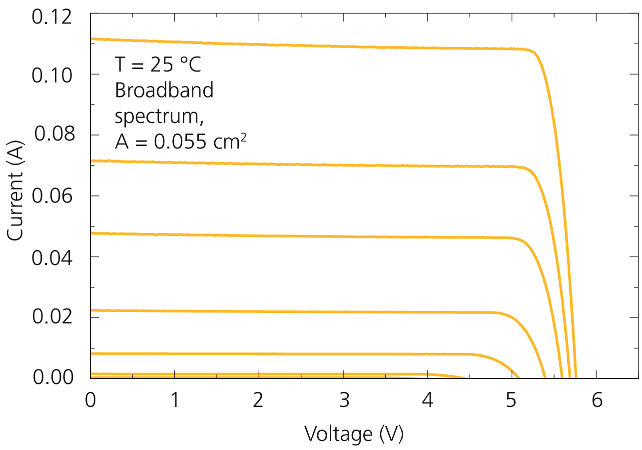
AI-Enhanced Design of High-Efficiency Photonic Power Converters for Telecommunications

Photonics and optoelectronics are key technologies for digitalization. The design of corresponding semiconductor components and the modeling of epitaxial processes that are needed for their fabrication can profit greatly from artificial intelligence (AI) methods within the framework of Industry 4.0. Omnipresent digitalization and automation as well as the Internet of Things require constant flows of energy and data. The emerging technology of photonic power transmission – also known as "power-by-light" – allows energy and data transfer to be combined in a single optical link and thus ensure electrically isolated, disturbance-free operation. By applying optical telecommunications wavelengths, the opportunities for applying such power-by-light systems can be extended to remote locations and enable unlimited energy supply over a distance.



Current-voltage characteristics of the 10-junction InGaAs PPCs under broadband illumination at different irradiance values.

In the "AIIR-Power" joint project, which is funded by the German Federal Ministry of Education and Research (BMBF), we are cooperating with our German and Canadian partners on AI-enhanced approaches for the design and fabrication of photonic power converters (PPC) for telecommunications wavelengths of around 1.5 µm. Within the project, Fraunhofer ISE is developing innovative PPC photovoltaic cells based on the III-V semiconductor, InGaAs(P). This is an optimal absorber material for this wavelength range.

For the first time, we have succeeded in producing an InGaAs multi-junction cell that consists of ten vertically stacked subcells. These are connected to each other in series via transparent tunnel diode layers. We ensured current matching of the series-connected subcells by accurate production of the subcell thicknesses. In addition, we can determine the subcell currents under different conditions as a result of a newly developed measurement procedure. Initial measurements of the current-voltage characteristic of the 10-junction cell under irradiation revealed output voltages exceeding 5 V (graph). As a result, lossy step-up voltage conversion can be avoided in application.

Furthermore, we are developing thin-film processing technology for InP-based semiconductor devices by adapting the thin-film technology that we had previously developed for GaAs-based devices. Production costs also play an important role in the usage of components. Particularly for InP-based components, the substrate costs represent a significant share of the total. To reduce these, we are developing so-called engineered substrates, in which a metamorphic InP layer is deposited onto a much less expensive GaAs substrate. We expect this to be advantageous for the application of the technology in industrial products.

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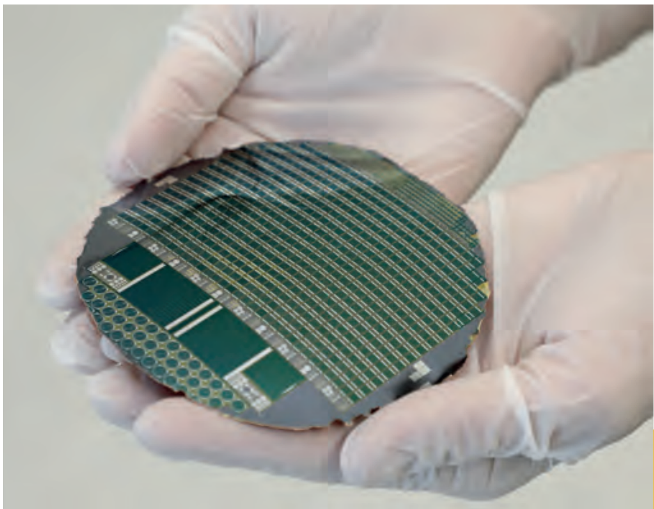
Flexible 4-inch wafer with InGaAs PPCs fabricated in thin-film technology.

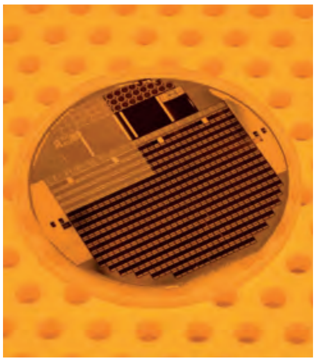


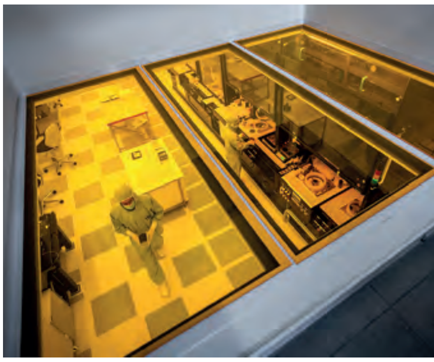
Development of High-Efficiency III-V Multi-Junction Solar Cells for Concentrator Photovoltaics

In the "50Prozent" project, which is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is developing high-efficiency multi-junction solar cells of III-V compound semiconductors for application under concentrated sunlight. The goal is to demonstrate an efficiency of 50 % for the first time. Theoretically, this ambitious target can be achieved with a solar cell that consists of four or more sub-cells. However, all materials and processes must be optimally matched to each other.

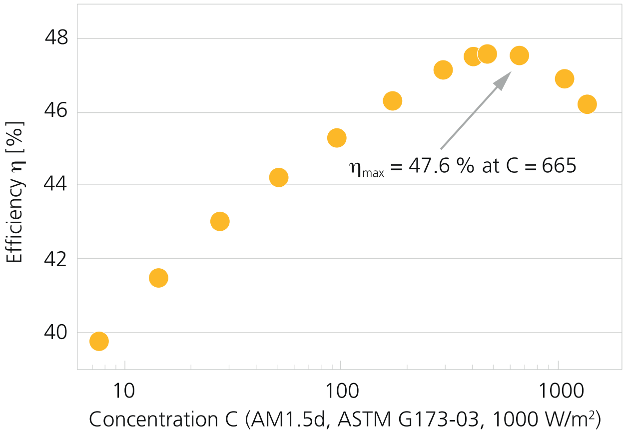
Based on theoretical calculations, we are further developing epitaxial processes for III-V crystals and are simultaneously optimizing the processing chain for metal contacts and anti-reflective layers. Even the electrical characterization must be newly developed for six-junction solar cells, in order to meet internationally recognized standards on measurement errors. In 2022, we reached an important milestone with the demonstration of the first solar cell in the world with an efficiency of 47.6 % (graph). This value was measured at a 665-fold concentration of sunlight with an AM 1.5d spectrum, i.e., at an irradiated power density of 66.5 W cm^{-2}. The solar cells are specially designed for these high light intensities and feature correspondingly low-resistance contact fingers. These are developed in the cleanroom of the new Center for High Efficiency Solar Cells (figure above). Excellent infrastructure for semiconductor processing is available there, such that we were able to produce minimally shading metal fingers with a thickness of only a few micrometers.

In the most recent developments, we are even attempting to conceal the metal fingers completely under a triangular, reflective cover. Combined with a four-layer HERPIN anti-reflective coating, we plan to suppress most of the parasitic reflection of light. The four-junction solar cells produced so far feature III-V semiconductor layers of GaInP, AlGaAs, GaInAsP and GaInAs, which absorb solar radiation between 350 nm and 1 750 nm. The two upper sub-cells are grown on a GaAs substrate, the lower two on InP. The cells are connected via a so-called direct semi-conductor bond. This complex production procedure is the prerequisite for achieving the excellent material quality that is needed for world record efficiencies. In a next step, we will introduce two further sub-cells into the structure, which increases the theoretical potential still further.





The concentrator solar cells (left) are processed in the clean-room of the new Center for High Efficiency Solar Cells (right), on wafers with a diameter of 100 mm.



In 2022, we set a new efficiency world record of 47.6 % under 665-fold concentration of sunlight. This was achieved with a wafer-bonded, four-junction solar cell made of GaInP/AlGaAs/GaInAsP/GaInAs.

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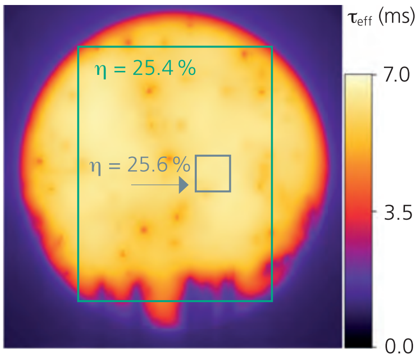
Epitaxially Grown Si Wafers for High-Efficiency Solar Cells



Lifetime map of epitaxially grown Si wafer with simulated cell efficiencies.

As the expansion of photovoltaics increase, cost aspects are playing an increasingly major role in PV production. A resource-conserving and cost-saving alternative to the conventional Si wafer is offered by the epitaxially grown Si wafer (EpiWafer). In this case, silicon grows directly from the gas phase on a template. This avoids the energy-intensive and loss-causing processing steps which lie between gas-phase deposition and the finished wafer for conventional Si wafers: deposition of polycrystalline silicon (poly-Si), melting the poly-Si, casting an ingot, wafering. Of course, this shortened processing route introduces new challenges: the quality of the template, cost-effective and high-quality Si epitaxy and the yield when removing the EpiWafer from the template.

At Fraunhofer ISE, we have established a process which allows the properties of the template and the removal process to be separated from those of the Si epitaxy. This makes it feasible to analyze the potential of the highest possible material qualities and to investigate new solar cell concepts. For this, we use chemically and mechanically polished Si wafers as the template. The Si epitaxy takes place in an ultra-clean microelectronic epitaxy reactor (figure below). Thereafter, the template is removed in a polishing process and the crystallographic and electrical quality of the free-standing Si epitaxial layer is investigated. Last year, we demonstrated excellent crystallographic quality (stack fault density < 1 cm^{-2}, displacement density < 100 cm^{-2}) and very long charge carrier lifetimes τ , (e.g., τ = 9.7 ms on 100 Ωcm p-doped material).

A further process which we have tested successfully is the growth of p-n junctions. The usage of these EpiWafer p-n junctions simplifies the solar cell processing, as no emitter diffusion is needed, and allows optimized doping profiles to be produced which are not possible with conventional diffusion.

To identify which of the many possible wafer doping options promise the highest cell efficiency, we carried out numerous cell simulations. Promising candidates are the TOPCoRE cells and p-doped Si wafers with low base doping. The figure (left) shows the lifetime map of an epitaxially grown Si wafer with a base resistance of 100 Ωcm. The simulation for the green, large-area region (6 x 8 cm^2) predicts a cell efficiency of 25.4 %, whereas the blue, best region (1 x 1 cm^2) features a cell efficiency of 25.6 %.

With our Si epitaxy reference route, we were able to offer a reliable baseline process to the start-up, NexWafe. The business has set itself the goal of upscaling the EpiWafer technology and uses our reference epitaxy to control the quality of all the individual steps in its EpiWafer processing chain.

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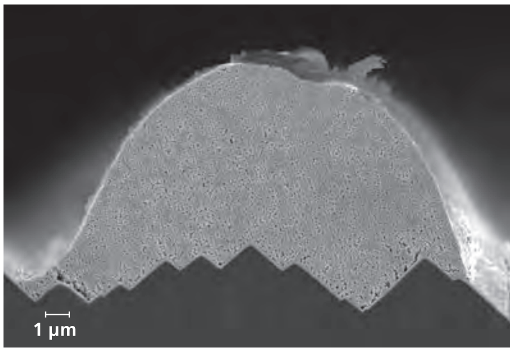
Wafer handling for the Si epitaxy reactor.

FlexTrail Fine-Line Printing for High-Efficiency Solar Cells with Resource-Conserving Material Input

The FlexTrail printing technique that was developed at Fraunhofer ISE is suitable for fine-line printing of numerous fluids. These include particle-based metal fluids, etching and pyrophoric media as well as color inks, polymers and ceramics. Compared to other printing techniques, FlexTrail is distinguished by high tolerance to the rheology of the printing media, particularly with respect to the viscosity. This means that both low-viscosity inks, e.g., for inkjet printing, and highly viscous pastes, e.g., for screen printing, can be applied with structure widths of 10 µm and less onto planar and textured substrates.



Scanning electron micrograph of a nano-silver contact finger's cross-section with an aspect ratio of 0.5.

Within the EU-funded "Bussard" project, Fraunhofer ISE is investigating FlexTrail as a direct metallization process to print front metal contacts based on silver nano-particles for silicon heterojunction solar cells (SHJ). FlexTrail printing allows metal contacts, as illustrated above in the scanning electron micrograph, to be produced in a single printing step. The average shading finger width of these metal contacts is (12.7 ± 0.4) µm and the average height is (6.4 ± 0.4) µm. The quotient of the two values is the aspect ratio of 0.5.

FlexTrail printing thus enables a very low silver consumption of only (9.4 ± 0.9) mg for a front contact grid without busbars that consists of 80 contact fingers with a length of 156 mm. This represents a saving of more than 60 % in silver, compared to the screen-printed reference. SHJ solar cells in the M2 format with FlexTrail-printed front contacts achieve efficiencies of up to (22.87 ± 0.01) %. This value is similar to the values which are obtained with screen-printed reference cells.

To demonstrate the development reached with Flextrail, we further processed SHJ solar cells with FlexTrail-printed contacts into monofacial mini-modules with an area of 200 mm x 200 mm. An industrial multi-wire connection approach was applied to do so. The modules achieve a maximum power of (5.0 ± 0.1) W. This is in accordance with the industrial standard and illustrates the high potential of FlexTrail printing to metallize high-efficiency solar cells with a low consumption of resources.

Up to now, we have implemented FlexTrail printing with a flexibly applicable printing head with one capillary tube, which we have integrated into various typical laboratory equipment environments, including a glovebox. The photo below, showing the single capillary tube, was taken during the printing process. Currently, a parallel printing head is being developed, which can be used for high-throughput metallization of high-efficiency (tandem) solar cells, but will also be relevant for other applications, for example in the printed electronics sector.

FlexTrail printing of a contact grid on a silicon heterojunction solar cell utilizing a single-capillary printing head.

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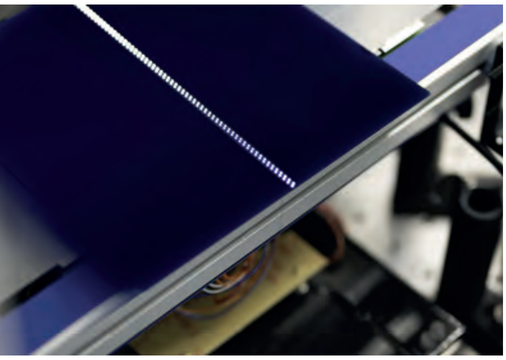
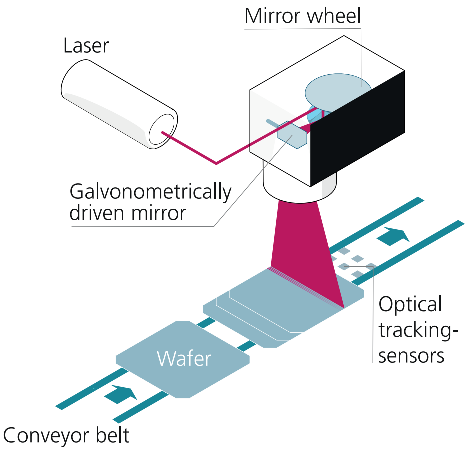
"On-the-Fly" Laser Processing with Highest Throughput



The laser generates several million contact openings per second while the wafer is continuously transported by a conveyor belt.

The production capacity for solar cells has increased rapidly in recent years. Although laser processing technology is an integral part of solar cell production, it is increasingly becoming a bottleneck to industrial production. Above all, the current transition to larger wafers, from M2 to M10 or M12, is accompanied by a reduction in throughput. The growing demands on speed can presently be met only by parallelization.



"On-the-fly" laser processing of solar cells using polygonal scanning technology.

The maximum speed with which the beam is scanned over the wafer is limited by the performance of the laser scanner. To date, mainly galvanometer scanners are used, which accelerate the beam up to 50 m/s with two highly dynamically driven mirrors. Polygon scanners, which can achieve significantly higher positioning speeds, present an alternative. A rotating polygonal mirror, consisting of several reflective facets, deflects the laser beam at up to 1 km/s over the processing area. A galvanometrically driven scan mirror positions the laser beam perpendicularly to the in-plane motion, so that a two-dimensional structure can be created.

Within the projects "PoLariS" and "NextTec", which are supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we developed a demonstrator for high-throughput laser processing of materials, which combines the polygon scanner with "on-the-fly" processing. "On-the-fly" refers to processing the workpiece while it is moving. A conveyor belt transports the solar cell underneath the laser scanner, with the solar cell being processed simultaneously. This means that linear or rotational positioning is not needed, so that acceleration and braking are avoided. Equipment idling time is reduced to a minimum.

For the first time, the concept unites the high-speed potential of the polygonal scanning technology with the throughput advantages of in-line processing. Due to the uniform rotational motion of the polygonal mirror, mirror facets with larger areas can also be used, which makes a clear increase in the focal length and thus the processing area feasible. We successfully demonstrated laser contact opening with a single processing track and a throughput of more than 15 000 M2 wafers per hour for the first time, while the cell quality and efficiency remained unchanged.

Our goal is to apply the concept also to other, more complex laser processes. Finer structures and, above all, greater accuracy are demanded for high-efficiency solar cells. To achieve these despite the high processing speeds, we are developing optical sensors which track the wafer position in real time and send correction signals to the laser scanner. In this way, the beam can follow fluctuations in speed during the process.

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Contactless Measurement of the Current-Voltage Characteristic of Silicon Solar Cells

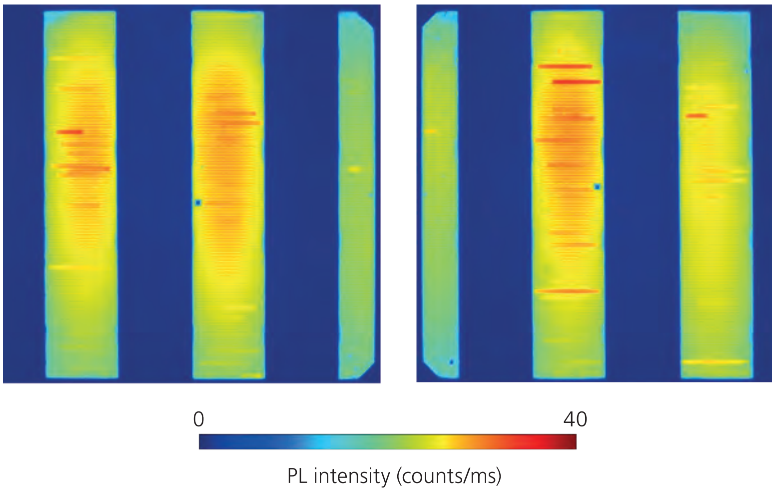
To mitigate threatening supply bottlenecks and reduce the manufacturing costs of silicon solar cells, high production throughput is needed – a decisive factor not only for PV expansion in Germany, but throughout the world. Within the "NextTec" project, which is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), a consortium of equipment manufacturers, producers of measurement technology and research institutes, headed by Fraunhofer ISE, has thus developed a proof of concept for a future production line with a throughput of 15000 to 20000 wafers per hour. This corresponds to a rate that is at least twice as high as that of currently applied production systems.

To increase the throughput for measuring the current-voltage characteristic (*IV* characteristic) – the most important characterization procedure during manufacturing – we have cooperated with the University of New South Wales, Australia to develop a novel process: It allows contactless measurement of the moving solar cell. Elimination of the time-critical and mechanically straining contacting proved to be advantageous particularly for multi-busbar solar cells, for which the contacting process is cost-intensive and decreases the homogeneity of illumination.

The procedure, for which Fraunhofer ISE has filed a patent claim, is based on the following four pillars:

- photoluminescence measurements with varying excitation intensity to determine the pseudo *IV*-characteristics
- contactless electroluminescence excitation spectroscopy to determine the relative quantum efficiency
- spectroscopic reflectance measurements to scale the relative to the absolute quantum efficiency
- photoluminescence measurements under partial shading to determine the internal series resistance of the solar cell (figure)

We have demonstrated the procedure for current types of solar cells (PERC, TOPCon, SHJ) in the laboratory. We determined good correlations between the data from contacted and contactless measurements for all performance parameters of the investigated solar cells: The deviations between the current-voltage parameters (j_{sc}, V_{oc}, *FF*, *pFF*, η) measured with and without contacting amounted to less than 2.5 $\%_{rel}$, making them comparable to typical absolute measurement uncertainty for accredited test laboratories. We were able to demonstrate that the contactless determination of current-voltage characteristics is feasible. The time needed for the measurement is limited only by the physics of the cell but not by the measurement technology.



Photoluminescence images of a partly shaded solar cell reveal defects in the metallization, among other features.

The procedure has numerous advantages: In addition to the higher throughput, it treats the solar cells more gently, leads to fewer parts subject to wear and also allows additional measurement data to be gathered. We will demonstrate these advantages in future research and development collaborations and finally develop the procedure to prototype and product stages.

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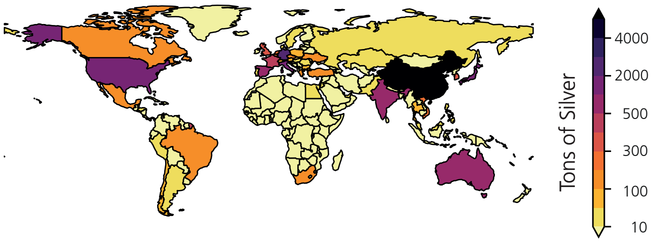
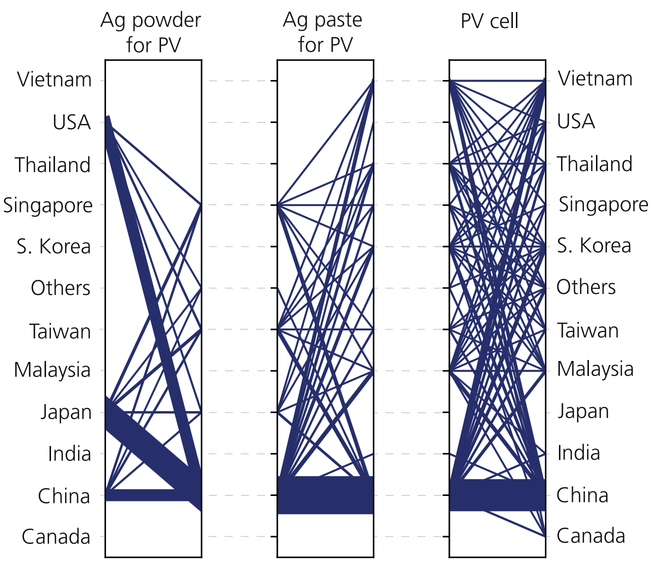
Risk Analysis to Increase the Resilience of Material Supply Chains



Tons of silver present in PV modules installed from 2000 to 2020. This amounts to 20 kilotons of silver embedded in PV installations throughout the world.



Ag supply chains for PV.

Resilient raw material supply chains are essential for the global economy. However, due to increasing specialization and complexity, they are becoming ever more vulnerable to supply risks. To avoid shortages, it is important to make businesses aware of this risk.

At Fraunhofer ISE, we have carried out a risk analysis for the supply chains of critical raw materials that are decisive for the value chain of crystalline silicon photovoltaics (PV). For example, we have modeled the distribution routes from mining to PV system installation for silver, which is used for the metal contacts of solar cells. Our model takes both the historic evolution over the past decades and also national differences into account. It provides information on the relevant supply patterns and the countries which play a key role in the transportation of silver. Furthermore, the ecological, social and governance (ESG) hotspots can be determined that are associated with each processing step.

There are diverse supply risks for photovoltaics: Firstly, the high market concentration in the manufacturing of silver powder and silver paste leads to the risk of delivery bottlenecks on the short and medium term. The market is dominated by only a few companies. Most of them have transferred their activities to China, where more than 85 % of the global silver paste production was concentrated in 2021. Secondly, the geopolitical tensions in the silver-producing countries have increased during the past twenty years. By applying the World Bank governance indicators, we estimate that about 35 % of the silver used in photovoltaics is transported through at least one country with a high risk of political instability or politically motivated violence. Thirdly, there is the danger that the rhythm of mine opening and production cannot keep up with the rapid expansion of PV that is expected in the near future. This demands an improvement in material utilization efficiency and the determination of silver reserves.

The solar cells which have been installed since 2 000 represent an important source of secondary silver. In Germany, for example, almost 3 000 tons of silver are concentrated in its installed PV modules. Our results are a first step in the direction of establishing more resilient and responsible supply chains – a topic, which will become increasingly important following the introduction of the EU sustainability regulations.

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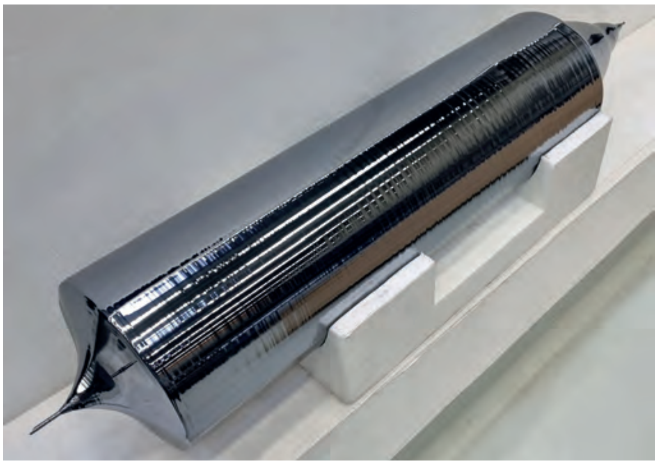
p-Type Si Solar Cells with Charge-Carrier-Selective Semiconductor Junctions and Passivated Contacts

The industrial production of solar cells is currently undergoing a transition to high-efficiency solar cells with charge-carrier-selective semiconductor junctions and passivated contacts. In particular, the high-temperature TOPCon (Tunnel Oxide Passivated Contact) concept developed at Fraunhofer ISE is gaining an increasing market share. The same holds for heterojunction solar cells (HJT). For these cells, manufacturers are replacing previously used p-type wafers by n-type Cz-Si wafers, which are 8 % to 10 % more expensive.

The goal of our research is to evaluate whether there are ways to continue using the significantly less expensive p-type Cz-Si wafers. If p-type Cz-Si material is processed almost identically to n-type material, a TOPCoRE solar cell (Tunnel Oxide Passivated Contact with Rear Emitter) with a semiconductor junction near the rear surface is created instead of a TOPCon solar cell with its semiconductor junction near the front surface. This means that long diffusion lengths are needed for minority charge carriers, if high efficiencies are to be achieved. If HJT solar cells are produced on p-type instead of n-type Cz-Si wafers, the semiconductor junction moves from the back to the front of the solar cell. However, if this low-temperature processing route is followed, charge-carrier-selective heterojunctions to amorphous silicon are located at both the front and the back of the crystalline Si wafer. As a result, long diffusion lengths are again decisive for the success of this type of solar cell. To make long diffusion lengths feasible on p-type Cz-Si material, we used gallium as the dopant and deliberately lowered the dopant concentration, without changing the manufacturing method or increasing the associated costs for p-type Cz-Si. The p-type material that was produced in this way was systematically evaluated along the complete length of the Cz-Si ingots – 10 000 wafers – with respect to its suitability for the high-efficiency solar cell concepts mentioned above.

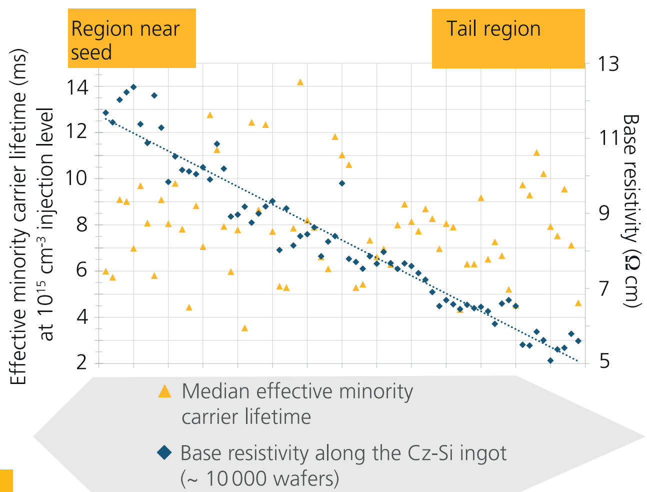


Typical Cz-Si monocrystal before wafer production (seed region is on the left).

The material features very long lifetimes in all regions of Cz-Si crystal growth. Due to the 2.6-fold higher mobility of the minority charge carriers in p-type material, the resulting diffusion lengths are superior to those of the n-type Cz-Si wafers typically used in industrial production.

After identical processing, TOPCoRE solar cells already now show an efficiency benefit of up to 0.2 % compared to n-type TOPCon solar cells. Together with the significantly lower wafer costs for p-type wafers, this results in a major cost advantage for industrial application.

For the HJT solar cells, the efficiency for the p-type material is still at least 0.2 % lower than for the n-type material. Here, further adaptations are needed to improve the fill factor and thus the economic viability.



Variation of base resistivity along the length of the Ga-doped Cz-Si ingot (boule) and corresponding effective minority carrier lifetime values.

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Successful Industrialization of the Matrix-Shingle Technology

Roofs and façades offer enormous, largely untapped potential to generate solar electricity. Their exploitation would make the ambitious expansion targets for the energy transition accessible. The matrix-shingle technology, as an innovative process to connect solar cells with each other, offers great advantages for this application: No gaps between cells are created with the matrix-shingle connection, so that the available area can be covered completely with solar cells. As a result, the active area is significantly larger than for conventional PV modules; the module efficiency increases. An adhesive electrically connects the cell strips of rectangular solar cells where they overlap each other. Cell connectors are not required, so that optical losses due to shading and resistance losses are lower. Shingled solar cells are connected without needing lead (Pb) as an additive. Furthermore, the homogeneous appearance of matrix-shingle modules means that very aesthetically attractive PV modules can be manufactured.

Together with its industrial partners, Fraunhofer ISE successfully transferred the matrix-shingle technology to industrial implementation within the "Shirkan" project, which was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). A stringer was developed that achieves a throughput of 12 500 shingle solar cells per hour. The first prototype of this matrix connection facility was taken into operation at Fraunhofer ISE and is available to industrial partners for constructing prototype modules.

The first series production of full-scale matrix-shingle modules was very successful. The stringer is also able to cope easily with flexible module dimensions, forms and coverage ratios for applications in building-integrated photovoltaics (BIPV). Our project partner, M10 Solar Equipment GmbH, won both the Intersolar Award 2022 and the German Innovation Prize 2022 for the production equipment concept. Fraunhofer ISE has developed different module concepts and compared them to conventional modules. These comparisons showed that, depending on the scenario, partially shaded matrix-shingle modules can generate a yield that is up to three times higher than that from conventional PV modules. Furthermore, cost calculations indicate that the manufacturing costs for matrix-shingle modules are not higher than those for conventional PV modules.

With these results, the foundations have been laid for constructing industrial production lines based on this innovative technology. Discussions with interested investors have been very encouraging, so that we assume that industrial implementation will start during the coming year.

Full-scale PV module with matrix-shingle technology (left). Matrix-shingle module with MorphoColor™ coating in terracotta red: The visually high-quality appearance is, in addition to the technical advantages, a unique selling point of the matrix-shingle technology (right).

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Automated Fault Detection and Optimized Operation Management for PV Power Plants

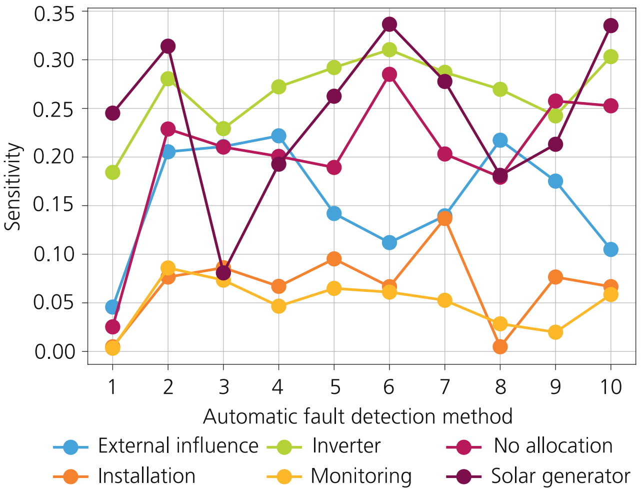
More than 2.2 million photovoltaic systems with a total power of 59 GWp were in operation in Germany at the end of 2021 and supplied around 9.8 % of the total, publicly generated power. As the operating age of the photovoltaic systems increases, (partial) breakdowns and aging effect become continually more frequent. An increased need for maintenance and decreasing solar yields are the result. As the degradation effects occur gradually, they could not be detected up to now with conventional monitoring systems. By contrast, the large number of installations and the numerous possible causes of defects associated with classic breakdowns pose major challenges to operation management.

In the "OptOM" project, which is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we are cooperating with Pohlen Solar GmbH and mondas GmbH to develop new methods for automatic monitoring of a large number of PV power plants. To do so, we are combining rule-based approaches and methods based on machine learning to identify the system outages that are associated with operating age, to classify them and to quantify the individual loss in yield. The goal is to develop an ecologically and economically sustainable strategy to operate the more than 3 000 PV power plants managed by Pohlen Solar GmbH.

In our tests, we have used the repair and maintenance logbooks for the systems from the installation portfolio as a reference to measure the accuracy of fault detection and determine the sensitivity of the different methods. The detection rate for all faults that affect the yield significantly is now around 99 %. By contrast, the large number of irrelevant error messages, inaccurate fault attribution and unnecessary on-site investigations has already been clearly reduced. In the next development steps, appropriate algorithms are planned to recognize correlations between unusual operating states and system breakdowns. This will enable photovoltaic power plant operators to prioritize suitable service work, before a breakdown occurs and yield is lost.

The procedures developed within the project were transferred directly to a production system and are now applied in real-time operation.

mondas GmbH has implemented the methods developed in the project in its software platform for technical monitoring. The web application developed in the project already supports Pohlen Solar GmbH in efficiently detecting faults, planning preventive maintenance campaigns and prioritizing repair efforts on the basis of the anticipated yield loss. In August 2021, a spin-off, Enmova GmbH, was founded to allow broader commercial usage of the project results. The new company offers high-performance IT solutions for digital operation management of photovoltaic power plants.



Sensitivity of ten different methods as a function of the fault category. The combination of all methods detects 99 % of all plant faults.

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Tapping the Potential of Agrivoltaics in Baden-Württemberg, Germany

Agrivoltaics (Agri-PV) unites photovoltaic generation of electricity and agriculture, creating synergistic effects without land-use conflicts. Within a project on the initial implementation phase of the agrivoltaic model region for Baden-Württemberg, Fraunhofer ISE has cooperated with 13 further project partners to construct and commence operation of two commercial and three research installations. The project is supported by two Ministries of the State of Baden-Württemberg, namely for the environment, climate and energy economy (UM) and for nutrition, rural areas and consumer protection (MLR). The goal is to gain as much knowledge as possible about different cultivated plants and locations. Furthermore, legal administrative hurdles to implementing an agrivoltaic-system are to be identified and addressed with the support of the Hochschule für öffentliche Verwaltung (University for Public Administration) in Kehl. The Landwirtschaftliche Technologiezentrum (agricultural technology center) in Augustenberg, the Kompetenzzentrum Obstbau Bodensee (Lake Constance orchard competence center) and the Staatliche Lehr- und Versuchsanstalt für Wein- und Obstbau (state teaching and experimental institute for viticulture and orchard-growing) in Weinberg are responsible for the agricultural investigations.

Our 239 kWp installation in Kressbronn near Lake Constance is the first agrivoltaic-system to be constructed, officially opened and connected to the grid within the project. At the same time, it is the first German electricity-generating system to be integrated into a completely commercial, apple orchard business. The system provides varying degrees of shade, having modules with two degrees of transparency (51 % and 40 %). Their effect on the eco-physiology of the apples is to be investigated, as are possible effects of pesticides on the PV modules.

Mainly apples and plums will grow under a further, completely covered system in Nussbach, where at least 710 kWp are planned. The modules are tracked, whereby one part of the installation will be optimized for electricity generation whereas the other will be controlled according to the plants' requirements. High harvest yields would mean that an agrivoltaic-system that is compatible with plant cultivation can also be constructed with standard PV modules. Compared to semi-transparent modules, this would bring the advantage of a clear cost reduction.

A 115 kWp system is currently being built in Heuchlingen with semi-transparent modules, where the availability of light will be around 70 %. It is intended to form a roof over berry shrubs and strawberries, and to influence the micro-climate positively by its closed design. The roof structure with an integrated drainage system can be used throughout the year to collect rainwater that is then stored and used for irrigation. In addition, management of the water circulation is intended to prevent infiltration of nitrates.

Modules of the same type as in Heuchlingen are also used in a 227 kWp installation in Bavendorf, where we are cooperating with the Kompetenzzentrum Obstbau Bodensee to investigate the effect of an agrivoltaic-system on organic farming, taking four different apple varieties as examples. The system consists of stationary and tracking sub-systems and is equipped with both stationary and tracked reference areas. Construction of a further 400 kWp system of the same structural design is planned for early 2023 in Augustenberg. Bifacial modules in the stationary part will form a roof over existing apple and pear trees; the sub-structure will also support nets to protect against insect pests.

The first Gala apples are growing beneath the agrivoltaic plant in Kressbronn.

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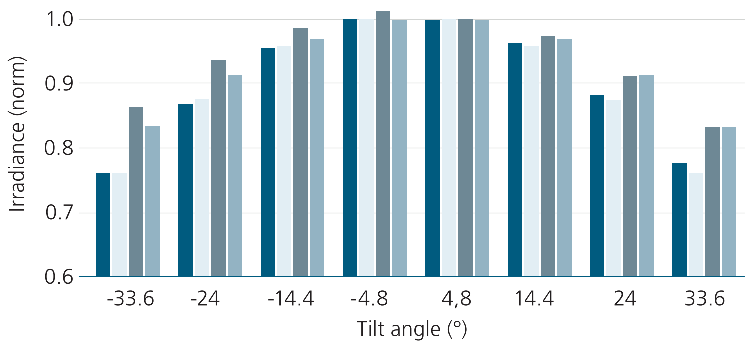
Test Methods for Integrated PV Applications, Illustrated with Vehicle-Integrated Photovoltaics

The integration of photovoltaics into different areas and applications opens up enormous potential but also demands careful analysis of the specific requirements. In particular, this applies to fundamental considerations concerning compliance with requirements in laws or standards on PV modules. In the case of vehicle-integrated PV (VIPV), for example, the compatibility with the usual vehicle authorization procedures must be investigated. Furthermore, established measurement and testing procedures for PV modules have to be re-evaluated in the context of new applications; the form, size, materials, requirements on long-term stability and the relative weighting of the considered module properties can deviate significantly from those for conventional PV power plants. For example, a uniform appearance over very long application periods is very relevant for building-integrated photovoltaics (BIPV).



Comparison of calculated and measured currents for single strings of a strongly curved module (radius of curvature 1 m), determined indoors with a solar simulator (flasher) and outdoors.

The development of adapted measurement and test procedures is a complex research area, which is very important for the success of integrated PV. At Fraunhofer ISE, we are engaged in laying the scientific foundations and also work within standardization bodies. In the "Lade-PV" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we have prepared the first fundamental comparison of requirements from vehicle technology (i.a. ISO 16750) with safety-relevant standards for modules (IEC 61730), to identify both synergistic effects and areas where modification is needed.

In the "3D" project, which is also supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we are developing methods to measure curved PV modules. To allow their electrical properties to be characterized comparably in different laboratories, new methods and correction procedures must be defined and standardized. This affects, for example, the definition of the reference plane in the module as well as the calculation-based adaptation of radiation which is not normally incident on the test object. Fraunhofer ISE is participating in international harmonization within the framework of IEC standardization by supporting an international round robin to measure curved modules and carrying out indoor/outdoor comparative measurements to verify the laboratory results for performance and angular dependence.

The measured data in the graph show the effect of a curved form on the module current. Each cell string of the module was connected and measured separately. In calculating the currents, the distance of the test object from the light source and the divergence of the light were taken into account. The calculation results agree well with the measurements. In the outermost strings, the deviation from outdoor measurement is largest, as there the angle difference between the object plane and the reference plane is greatest. This can be compensated by correction factors. The prerequisite for this is that the beam path of the laboratory illumination source (flasher) is as parallel and homogeneous as possible, and well described.

Testing a VIPV Module.

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Colored Glass Covers for Solar-Thermal Collectors

Generating heat with solar-thermal collectors is an important component in achieving a completely renewable energy supply in Germany. However, concepts for collectors that could be well integrated aesthetically into buildings had been lacking up to now. This applies not only to new buildings but particularly to historic town centers and heritage buildings. State-of-the-art technologies feature either low color saturation or large losses in efficiency.

Based on the MorphoColor® technology, which has been patented by Fraunhofer ISE, we developed colored glass covers for solar-thermal collectors in the "Farbkollektor" project supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The panes feature three advantages: high color saturation, high light transmittance – 90 % relative to conventional collectors – and good color stability under different viewing angles.

The inspiration for the MorphoColor® coating came from the microstructures on the wings of the morpho butterfly, which lives in the forests of Central and South America. In our approach, the colored effect results from the interaction between geometrical structures and interference coatings on the inner surface of the glass cover.

We identified optimal surface structures and interference coatings by 3D simulation of the optical properties. After optimizing the coatings with laboratory equipment, the coating process was transferred to the industrial coater operated by our project partner, AGC Interpane. We succeeded in demonstrating the stability of the coating for the application in a collector and in determining the efficiency. For the colors of red, green and blue, we determined an efficiency exceeding 90 % of that for an uncoated reference pane. In t he Solar KEYMARK Committee, a simplified procedure was defined to certify collectors with MorphoColor® panes, which supports their commercial exploitation. The prerequisite is a Solar KEYMARK certification of a flat-plate collector of the same construction. Furthermore, we have prepared demonstration collectors in colors of silver-grey and gold. Subsequently, our industrial partner, AGC Interpane, produced about 120 m² of colored glass covers, which the collector manufacturer SIKO used to equip solar-thermal collectors. They were installed in two pilot systems in Freiburg, Germany and Jenbach, Austria and their performance has been monitored and evaluated.

In addition to the roof-mounted installation shown below, the colored collectors developed in the project are suitable to design attractive, solar-thermal building façades.

A colored solar thermal collector exposed on the outdoor test stand at Fraunhofer ISE.

Pilot installation with colored solar thermal collectors in Freiburg St. Georgen.

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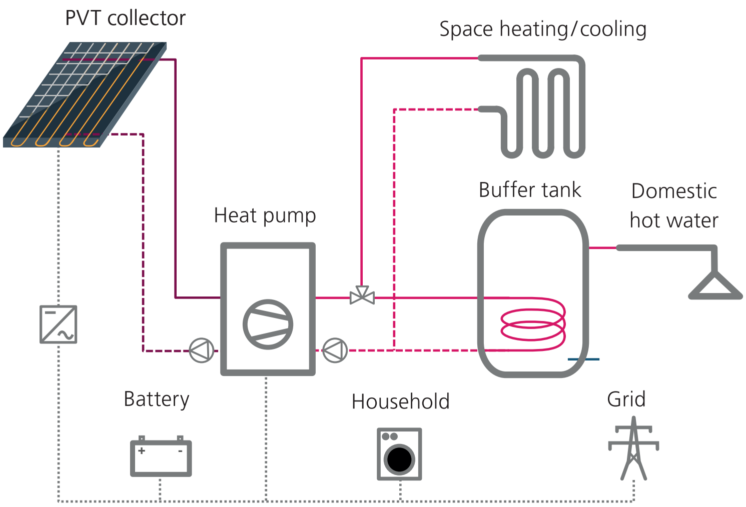
integraTE – Innovative System Solutions for Space Heating and Cooling

The combined application of renewable energy from different sources is an important factor in achieving CO_2 savings in the building sector. This applies both for the existing building stock and for new buildings. One innovative system solution is the combination of a heat pump and photovoltaic-thermal collectors (PVT). Both the heat and the electricity generated by the PVT collectors are used as energy sources for the heat pump. The combination of PVT with a heat pump as a system concept offers promising opportunities for development and optimization. These include, for example, the different variants for hydraulic connection with additional energy storage units at different points of the circuit, the different area dimensioning of the collectors and extended operating modes for the heat pumps.

Within the "integraTE" project, which is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is providing scientific support to the suppliers of such systems. The goals are to demonstrate its technological readiness, identify potential for improvement and prepare the market further for these highly effective heating supply solutions. The project encompasses simulations that were carried out by the Institute for Solar Energy Research Hameln as well as the market analysis that was prepared by IGTE at the University of Stuttgart. Fraunhofer ISE is participating with a measurement campaign that is analyzing the performance of nine installations in the field. The data and knowledge gained are processed under the leadership of our media partner, Solrico, and published in professional articles – e.g. in training documents for the installation tradespeople, for professional associations such as the Bundesverband Wärmepumpe (BWP – German Association for Heat Pumps), the Bundesverband Solarwirtschaft e.V. (German Association for the Solar Economy) and the Bundesverband der Deutschen Heizungsindustrie (BDH – German Association for the Heating Industry). The material – information on yields, operating results and other analyses – is also available under pvt-energie.de for presentation at scientific conferences or also marketing activities and media reports.

Demonstration system with a PVT collector array.



Schematic diagram of a simple combination of a heat pump and PVT collectors in a heating system.

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LC150 – Propane Refrigerant Circuits with Significantly Reduced Fluid Volumes

Heat pumps as a central component of the heating transition.

The demand for heat pumps, being key components for the heating transition, will increase continually in the coming years. This makes it all the more important to investigate sustainable refrigerant solutions. Propane offers a high potential as a refrigerant, as it features very good thermodynamic properties and has only a small effect as a greenhouse gas. Its combustibility is disadvantageous. To minimize this disadvantage, a promising approach is to reduce the mass of the incorporated refrigerant to less than 150 g.

Since the end of 2020, Fraunhofer ISE has been cooperating with leading European heat pump manufacturers within the "LC150" (Low Charge 150 g) project that is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The consortium is working on a standardized cooling circuit for heat pumps which enables high efficiency while needing only small amounts of refrigerant. In more than 5000 measurements, already eighteen cooling circuit candidates have been tested in a largely automated measurement facility in the Center for Heating and Cooling Technology at Fraunhofer ISE. The goal is to identify the best combination of evaporator, condenser and compressor and to tap potentials for a further reduction in the amount of refrigerant needed. In the targeted power class of 6 to 10 kW, we have already achieved a seasonal coefficient of performance (SCOP) with several test objects which meets the requirements of the German Federal Office for Economic Affairs and Export Control (BAFA) for subsidies. The best test candidate to date achieved a heating power of 12.5 kW with a seasonal efficiency of 4.7 (SCOP) and a refrigerant charge of 124 g.

At the end of the project, many different cooling circuit configurations will have been subjected to the testing procedure. This provides the research team with an enormous pool of data which is available for the evaluation and dimensioning of heat pumps by simulation.

With the reduction of the amount of propane refrigerant by 70 % to 80 % compared to the state of the art, and the standardization of production, the LC150 project has laid the foundation for the rapid and uncomplicated market introduction of efficient, cost-effective heat pumps to the residential market.

Due to the successively increasing proportion of renewable energy in the electricity mixture, a CO_2 savings potential of 80 % to 90 % compared to gas heating can result by 2030.

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In a broad measurement campaign, dozens of heat pump component combinations are tested with different operating parameters.

Automated Generation of Digital Hydraulic Schematics

The replacement of fossil-fueled heating systems is essential to reach the climate-relevant political goals in the building sector. One challenge in doing so is the lack of resources in the installation trade, which can be addressed by the digitalization of certain processes. A central research area in this context is the automated identification of technical building plant.

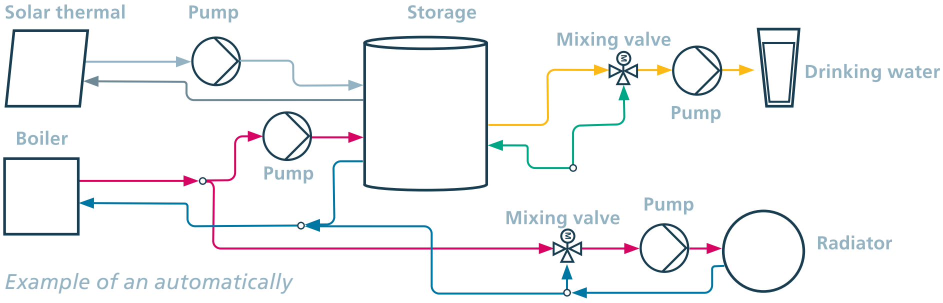
Within the "DiBesAnSHK" project that is funded by the German Federal Ministry of Education and Research (BMBF), Fraunhofer ISE has developed software which allows automated, valid system configurations to be derived on the basis of a set of main components (converters, storage units and transfer systems). To do so, we follow a two-stage approach: In the first step, the components are connected to form a logical energy flow diagram. In a second step, the hydraulic components (valves, pumps, flap valves) are added and practically applicable hydraulic diagrams are generated. The goal is to use the determined and digitally represented system configurations as the basis for detailed planning and dimensioning, and subsequently to generate an automated offer.

The starting point to generate Heating, Ventilation and Air Conditioning (HVAC) schematics is the specification of the main components that they contain and their connections, i.e., the energy generators and transfer systems are set. The type of input and output media is defined for each of these components. This initial information could be entered manually or generated automatically by AI-supported object identification based on video and photo documentation of the technical plant room. The software then generates possible energy-flow configurations from the information about the components and their connections. These energy flow diagrams can already serve to analyze or simulate a system in an early planning stage. Subsequently, the software determines the associated hydraulic circuits for a selected energy flow diagram. Pumps,

Photographic documentation of existing systems.

valves and branches are automatically added and additional connections for feed and return flows are created. We have implemented a prototype of the two-stage procedure in Python and visualized the resulting graphs using a Javascript library.

In the "DiBesAnSHK" project, we initially focused on simple building technical systems that are common in the existing building stock and on fundamental hydraulic circuits. We have not yet treated ventilation or cooling technology. In the further course of the developments, however, we will address more complex systems. In addition, the automated analysis and selection of renovation concepts is planned as a further application case.



Example of an automatically generated HVAC schematics.

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Higher Efficiency with an Air Wall – Reduction of Convective Losses in Solar Thermal Power Plants

In solar tower power plants, large areas of reflectors concentrate sunlight onto a central receiver to cause very high temperatures there. In existing commercial power plants, the resulting thermal energy is primarily used to generate electricity. During the day, the heat can be converted directly into electricity or stored in large tanks filled with molten salt. In this way, electricity can be provided as required during high-demand periods, particularly during the evening after sunset.

Numerous international research projects are working on increasing the fluid temperature in the receiver, from currently approximately 650 °C, to 1 000 °C and higher. This leads to a substantial increase in the efficiency of converting thermal energy to electricity, and also makes chemical high-temperature processes feasible, e.g., as required for purely solar thermochemical generation of hydrogen, synthetic fuels and cement.

Operation of a test mock-up of a solar thermal cavity receiver. The nozzles of an invisible air wall are located above and below the receiver opening.

Particular attention is being paid to the reduction of thermal losses, as unwanted convection and release of hot air from the receiver results in losses of around 7 % of the absorbed radiation in existing commercial power plants. Without suitable preventive measures, the thermal losses would increase strongly if the operating temperatures were raised any further.

An obvious way to completely suppress convective heat loss from the receiver would be to use a window of a material that is stable at high temperatures. However, due to the prevailing extreme radiative and thermal loads, attempts to produce a window with a satisfactory lifetime have been unsuccessful to date. As an alternative to a window (e.g., of quartz glass), the loss of hot air from the receiver can be strongly reduced with a so-called air wall. Nozzles create a rapid, strongly localized air current over the entire receiver aperture area which separates the region with hot air from the surrounding ambient air. This strongly reduces the unwanted convective heat loss. On the one hand, the simple and cost-effective installation into new or existing systems is one advantage of using an air wall. On the other hand, it does not attenuate the transmitted radiation by absorption or soiling, and it is not subject to thermal stresses or material defects, in contrast to a solid-state window.

Due to the high complexity of the fluid-dynamic problem, it has not yet been possible to reliably estimate the performance improvement achieved with an air wall by numerical simulation alone. Within the "HelioGlow" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE has thus cooperated with an industrial partner to construct an outdoor test stand for a full-scale solar thermal cavity receiver and equip it with an air wall system. To enable reproducible measurements, the solar radiation is replaced by electric heating elements. In numerous tests of the air wall under variable realistic conditions, a 30 % reduction of the convective heat losses from the receiver was achieved. The demonstrated reduction of thermal losses in this magnitude proves the commercial and economic viability of applying the air wall technology to solar tower power plants.

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High Temperature Heat Pumps for Industry

Reduction of greenhouse gas emissions and more efficient utilization of fossil fuels are very important to achieve the climate goals. With a share of approximately 57 % of the total energy consumption in Germany, a sustainable supply of heat and cooling energy represents a large potential for savings. High-temperature heat pumps (HTHP) present a technical alternative to combustion processes for supplying process heat and steam, and provide an opportunity to reduce CO_2 emissions and dependence on fossil fuels.

Over the past two years, we have extended our research activities at Fraunhofer ISE by adding the topic of industrial heat pumps for temperatures exceeding 80 °C. We are currently developing these further in two large research projects, which both focus on natural refrigerants. For example, hydrocarbons such as propane have already become successfully established for domestic heat pumps. On this basis, in our research activities we are now investigating how large-scale heat pumps for industrial applications can be operated safely and efficiently with hydrocarbons.

The "KETEC" project on a research platform for cooling and energy technology, which is funded by the German Federal Ministry of Education and Research (BMBF), with Fraunhofer ISE, TU Chemnitz and ILK Dresden as the project partners, offers an opportunity to demonstrate this. Within the project, we are constructing a heat pump circuit with butane, with which we can demonstrate different configurations of e.g. an economizer, a flash tank or parallel compression under operating conditions: the sink temperature can be raised up to 150 °C, dynamic changes in the sources are simulated with a source module and measurements can reveal the advantages and disadvantages of the corresponding configuration. During the further course of the project, the test stand will serve as a training object.

Within the "FernWP" project on district heating and process heat supply by heat pumps to replace coal combustion, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we are investigating the concrete integration into existing district heating systems and industrial processes. Initially, we are evaluating different heat pump circuits and refrigerants for this type of application. In cooperation with the Fraunhofer Institutes IEG and ISI, the Cottbus municipal utility (Stadtwerke), Johnson Controls, Gesmex and AGFW, the goal is to take a large-scale heat pump for district heating into operation on the site of a coal-fired power station. In addition, we are using a laboratory mock-up to evaluate different components and circuits to increase the efficiency. For example, we are investigating different industrial processes by applying a pinch analysis and are evaluating the suitability and the correct integration point for a heat pump.

Butane high temperature heat pump manufactured by Johnson Controls.

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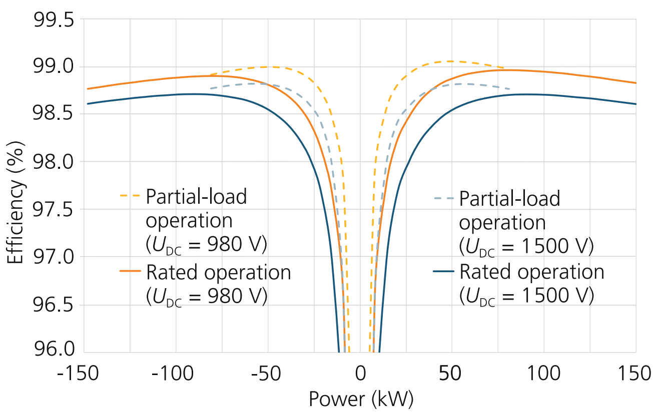
Power Electronics for Stationary Battery Storage Systems with up to 1 500 V Input Voltage

As the energy transition proceeds, the proportion of fluctuating, renewable energy in the energy mix is increasing. The development of energy storage units thus plays a central role. Within the "HYBAT" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is cooperating with BorgWarner AKASOL AG, HYDAC Cooling GmbH and the TU Dresden to develop a cost-optimized, hybrid battery storage solution for stationary applications.



Optimization of the inverter efficiency for the partial-load range.

We are focusing on the hardware development of bidirectional power electronics with a maximum input voltage of 1 500 V and a nominal power of 150 kW. In contrast to photovoltaic inverters, the rated power of battery storage systems must also be provided for maximal DC-link voltage. The constructed system is intended to make the present trend toward higher battery system voltages feasible. Due to the higher voltage, the battery modules and the power electronics have to conduct lower currents for the same power. This results in smaller system components and lower thermal losses. The system consists of an inverter as well as two DC/DC converters for the high-power and the high-energy battery modules. The different battery modules ensure optimal utilization and aging of the batteries for different load profiles.

The inverter consists of hybrid ANPC power semiconductor modules, which form a 3-level topology. It is composed of four cost-effective, slowly switching Si IGBTs (50 Hz) and two fast switching (48 kHz) SiC MOSFETs. This leads to a more cost-effective design with high switching frequency.

To optimize the partial-load range, we developed a multi-stage design for both the inverter and the DC/DC converter. This means that two output bridges are connected in parallel in each case, whereby one of them can be deactivated for the partial-load range. The partial-load range is particularly important in battery systems, as only lower charging powers are possible with batteries as the state of charge increases.

To evaluate the newly developed system components and validate the hybrid battery management of the storage element, we have built up a fully automated, permanent test stand in the Multi-Megawatt Laboratory of the Center for Power Electronics and Sustainable Grids at Fraunhofer ISE. We use this to evaluate the system properties of the hybrid lithium-ion battery storage solution with 1 500 V systems technology, innovative thermal management and self-optimizing operation management.

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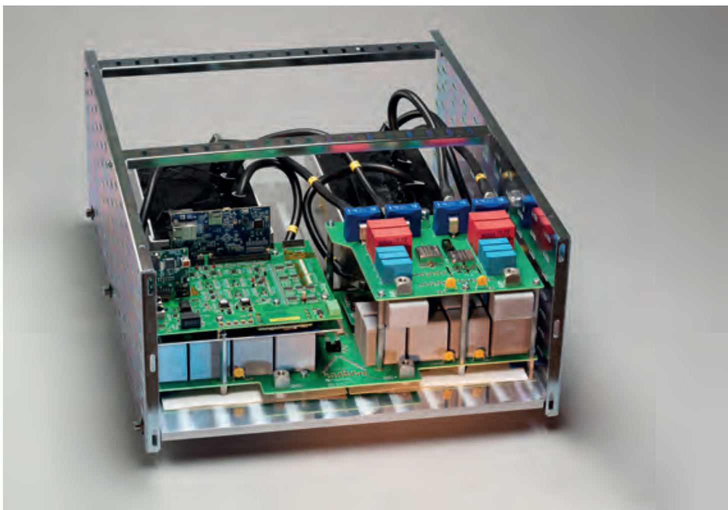
2-phase DC/DC converter with 150 kW power, 48 kHz switching frequency and input voltage of up to 1 500 V.

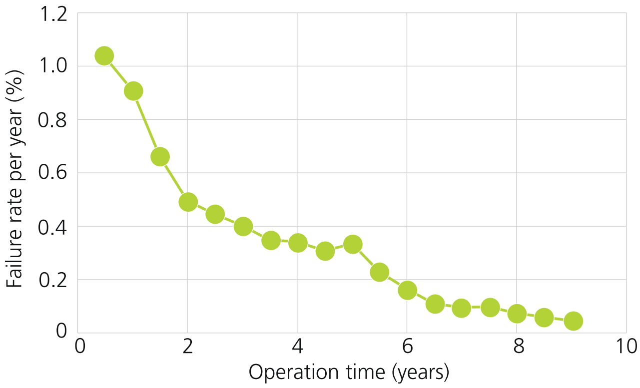


Field Data and Failure Analysis for Higher Reliability of PV Inverters

Inverters are key components for the transition from conventional to renewable electricity generation. However, they are among the system components with the highest failure rates and service costs. Whereas PV modules are designed for operating periods of twenty to thirty years, inverters usually reach an average lifetime of only ten to fifteen years.

Within the "power-4re" project, which is funded internally by the Fraunhofer-Gesellschaft, we have studied failure characteristics, sub-components and device-internal operating conditions, in order to identify options that can be taken to improve the reliability and lifetime of inverters. By analyzing field data for a string and a central inverter product line with an installed power of more than 19 GW and operating periods of up to ten years, we were able to identify semiconductor modules and electro-mechanical switches as the main components leading to failure. The variation of failure rates over the lifetime of these components shows a significant early-failure feature. On the one hand, this can be interpreted as a sign of quality, as known aging mechanisms such as bond wire lift-off and heel cracking play only a minor role. On the other hand, the results imply that common in-line or end-of-line tests during inverter production do not detect these early failures. Better understanding of the failure mechanisms and adaptation of the tests could thus contribute to improved inverter reliability.

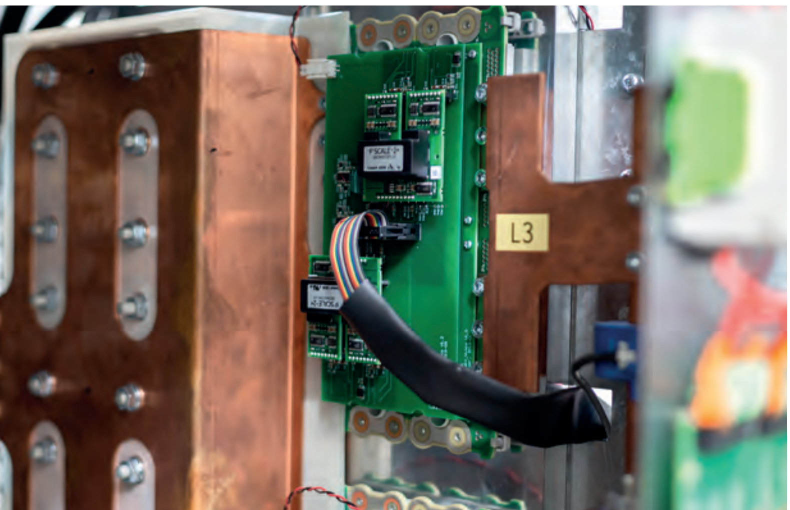
The failure rates increase in the Central European climate during the summer months, which are characterized by high absolute air humidity. Furthermore, around one third of the failures occur during or shortly after the initialization process for the inverter at low generated power values. With temperature and humidity sensors as well as power measurements,



Variation of the annual failure rate of a string inverter product line as a function of lifetime.

we have monitored the micro-climate within several string and central inverters. We demonstrated that the relative humidity inside the housing reached a maximum when initialization commenced. This suggests that humidity is an essential driver for the observed early failures. Possible failure mechanisms in semiconductor modules include dendrite formation due to electrochemical migration and deformation of electric fields at the edges of chips due to water molecules which lead to an insulation breakdown.

Based on the measured micro-climates, we are initially defining typical load scenarios for PV inverters in Central Europe. In the next step, we will derive a multi-modal stress test which accelerates humidity-induced failure mechanisms and thus enables the identification of reliable inverters for the future.



Semiconductor and driver module of a central inverter.

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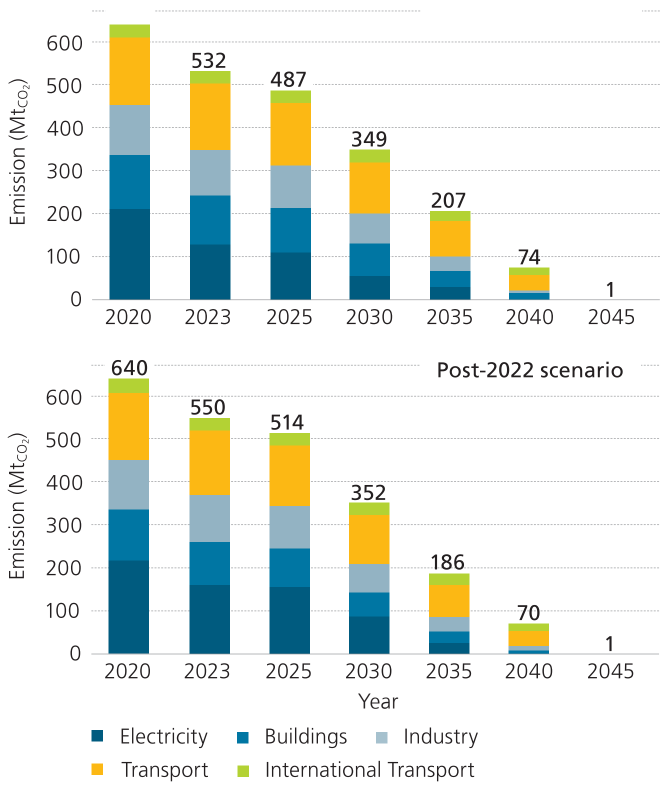
Transformation Paths for the Energy Transition under Changed Boundary Conditions

The energy world and public perception of the energy transition have changed in 2021 and 2022: Climate neutrality in 2045, the war in the Ukraine, the associated energy price increases and the increasingly obvious effects of climate change have influenced the energy-political discussion dramatically – and thus the possible transformation paths for the German and European energy system toward climate neutrality. How should it now proceed? How should the transformation paths be adapted to these changes?



CO_2 emissions from the energy economy resulting from REMod models of transformation paths for Germany.

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With the breadth of energy economics and energy systems analysis represented by the project partners and its interdisciplinary character, the "Copernicus-Ariadne" project is unique in its ability to analyze the dramatic changes of the past two years and to develop solution strategies.

In the "Copernicus-Ariadne" project, which is funded by the German Federal Ministry of Education and Research (BMBF), researchers at Fraunhofer ISE have developed the analytical methods for possible transformation paths further. The work has focused on developments of the REMod energy system model, which represents the German energy system and encompasses all types of technology as well as demand and costs.

To be specific, the supply security and changes in the safety position were analyzed last year. Within the "Copernicus-Ariadne" project, Fraunhofer ISE is analyzing how paths compatible with climate neutrality can react to the energy price dynamics, e.g., by saving larger amounts of natural gas and replacing it by renewable technology. The results show that savings in natural gas can only be compensated by a higher consumption of coal and oil. However, the consequence would be a somewhat weaker reduction in CO_2 emissions during the coming five years. Simultaneously, very high expansion rates for renewable energy result, which are 5 % to 8 % higher than the current, very ambitious plans. This leads to the conclusion that the current situation more strongly forces businesses to develop short-term strategies to reduce CO_2 emissions, above all by using green electricity. The quantitative structures from REMod modeling can provide important information to our clients and guide their own goals and efforts.

A further new feature of the REMod analyses is that the model was developed further to take the effects on the grid infrastructure and on individual German States into account. This makes it possible to specify the role and contributions of specific technologies in individual regions more accurately, allowing developments and measures to be derived for the individual States.

Bidirectional Charging – Exploiting the Full Potential of Electromobility

Electromobility is a key technology to decarbonize the transport sector – a research area which we have been addressing at Fraunhofer ISE for more than a decade. It encompasses efficient power electronics, battery technologies, communications interfaces and the grid integration of electric vehicles, as well as innovative business models and operation management concepts, which we evaluate in field tests. Following the first projects with prototypical implementations, the technology is now commercially mature and the focus is on large-scale applications with fleets of vehicles. We were able to reach an important milestone with the "LamA" research project on charging at the workplace.

Intelligently controlled charging stations were tested during the practical test at the end of the "LamA" project on charging at the workplace.

Within the project, the Fraunhofer-Gesellschaft cooperated with partners to install a total of 480 charging stations at 36 Fraunhofer Institutes throughout Germany, with Freiburg being one of three flagship locations. In the concluding practical test, Fraunhofer ISE and bnNETZE, the local grid operator, proved that intelligent control in the grid management system protects the distribution grid against overload when many users want to charge their vehicles simultaneously.

In the follow-up project, "LamA²", the researchers are now directing their attention to one of the next steps in electromobility, in which bidirectionally chargeable electric vehicles are to become mobile battery storage units for the electricity grid. In addition to regulatory questions, interoperability is a further field of research. When electric vehicles feed charge into the smart grid according to a grid-supportive protocol, information must be exchanged between the various actors. At the Digital Grid Lab of Fraunhofer ISE, we have set up a hardware-in-the-loop test stand for bidirectional charging infrastructure. We can test the interoperability there from the distribution grid operator up to the charging station with the help of digital twins of the electric vehicles and our laboratory control center. To do so, we are developing and testing the most recent communications protocols such as ISO 15118-20, OCPP 2.0.1 with current extensions and EEBus.

Furthermore, we have done field testing of bidirectional charging for two application cases as part of a development contract for TransnetBW, a transmission grid operator. Electricity from the grid is used for charging when a large share of renewable energy (RE) is available. This stored RE electricity can be provided again later as needed for the local company grid or other vehicles. By transferring charge back from vehicles into the grid, peak loads can be actively flattened for the consumer, reducing grid service fees. A predictive optimization algorithm developed by Fraunhofer ISE, which provides charging schedules as a cloud service, makes this feasible.

Hardware-in-the-loop tests for bidirectional charging in the Digital Grid Lab.

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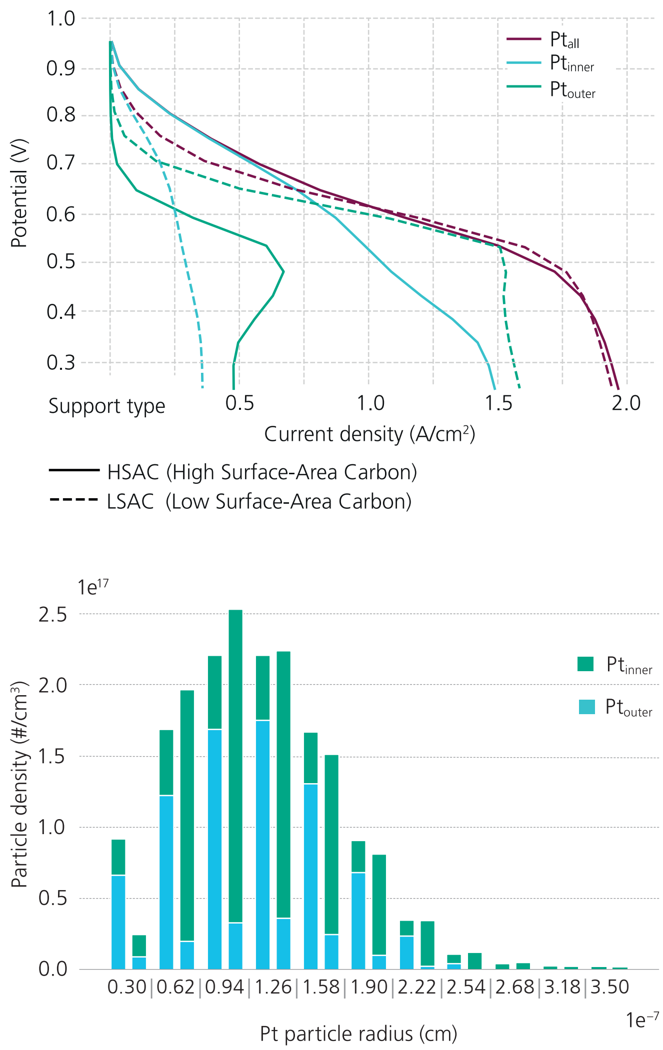
Performance and Aging of the Membrane Electrode Assembly of Mobile Fuel Cells



Simulation of the effect of the carbon structure on the platinum distribution and the polarization curve, taking two different platinum-carbon catalysts as examples.

One of the major challenges to make fuel cell technology competitive is to reduce the amount of expensive platinum used as catalyst. To ensure that reducing the amount of platinum does not compromise either the cell performance or its long-term stability, the electrode structure must be optimized.

Within the "FC-CAT" and "FC-RAT" projects, which are funded by the German Federal Ministry of Education and Research (BMBF), we develop models to reproduce the correlated interactions between performance and aging on the one hand and between materials and structure on the other. The catalyst layer consists of aggregates of carbon particles decorated with platinum, which are held together by an ionomer network that acts as protonic phase. In this configuration, not every platinum particle is in contact with the ionomer, so may be inactive for the electrochemical reaction, depending on the water content of the electrode. However, direct contact of the ionomer with the platinum particle causes unwanted partial blockage of active sites by the sulfonic acid groups of the ionomer side chains. Consequently, the platinum particles should remain at a distance of a few nanometers from the ionomer, so that – in combination with water – a high proton concentration at the platinum surface is guaranteed, but no poisoning results. Thus, the positioning of the platinum nano-particles on the carbon support structure is decisive when the amount of platinum is reduced.

Our model is based on a particle size distribution (PSD) of the platinum (Pt). A distinction is made between particles on the support surface, which can be in contact with the ionomer, and particles inside the meso-pores of the support, which are inaccessible to the ionomer. The model couples this structural information with the physical-electrochemical processes which describe current generation but also degradation effects on the basis of kinetics and mass transport equations. We are thus able to simulate the effect of the platinum positioning under different operating conditions on cell performance and aging. The figures show a simulated polarization curve together with the proportion of current generation for two platinum classifications (above) and the PSD used for the simulation (below).

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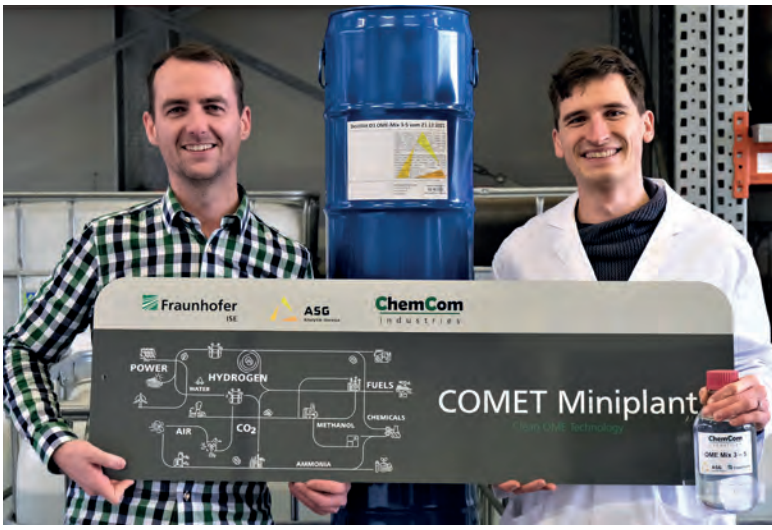
Synthetic Fuels for Sustainable Mobility – the π-COMET® Technology of Fraunhofer ISE

Whereas the trend for cars is toward electric vehicles, liquid fuels continue to dominate in heavy transport, shipping and aviation as well as off-road machines for mining and agriculture. Indeed, the meta-study on hydrogen, evaluating energy system studies and commissioned by the German National Hydrogen Council (Wasserstoffrat), documents that the energy transition can only be successful if accompanied by global trade of H_2 and PtX products. Oxymethylene ethers (OME) used as e-fuels can significantly reduce the local emissions of soot and nitrogen oxides from diesel engines. By sustainably producing OME in a PtX value chain, it is possible to reduce the greenhouse gas emissions by more than 86 % in comparison to diesel fuel – from 209 g (CO_{2eq}) km^{-1} diesel to 29 g (CO_{2eq}) km^{-1} OME. In a carbon-neutral scenario with OME as a substitute for fossil diesel fuel, the reduction of CO_2 equivalents can be increased to 95 %, according to our ecological balance. This approach thus possesses enormous potential to reduce emissions in the transport sector.



The scientists, Franz Mantei from Fraunhofer ISE (right) and Christian Schwarz from ASG Analytik Services AG (left), present the Power-to-OME value chain.

One hurdle for large-scale industrial production of OME to date was the water management in the synthesis process. In the project, "π-COMET® – Process Intensified Clean OME Technology", Fraunhofer ISE has cooperated with its industrial partners, ChemCom Industries B.V. and ASG Analytik-Service AG, to develop an innovative technical solution which makes an OME production process feasible on an industrial scale. The π-COMET® concept, for which a patent claim has been filed, concentrates on removing the water after the OME synthesis in a reactive distillation column and thereby solves the water management problem using state-of-the-art components. There is no longer any need for the previously used extraction and adsorption or membrane-based technology, which would delay upscaling. The process structure and the operating conditions for the reactive distillation column make significantly higher yields and selectivity feasible in the OME synthesis, which lead to increased efficiency in the overall process. After providing a proof of concept of the process, the project team successfully demonstrated the integrated process on a technical demonstration scale. To do so, the newly developed π-COMET® pilot plant was used, which was connected to an industrial pilot plant for the reactive distillation and product purification. The OME final product reached the quality specified by the DIN pre-standards. Fraunhofer ISE is currently working together with the project partners on the engineering of the first European OME production based on the π-COMET® process concept, with a production rate of approximately 1 t/h and located in Delfzijl, the Netherlands. The partners are aiming to commission the plant by 2025. It should serve as a reference plant for further upscaling.

Pure OME, BlueGrade® according to the pre-normative technical specification, DIN/TS 51699.

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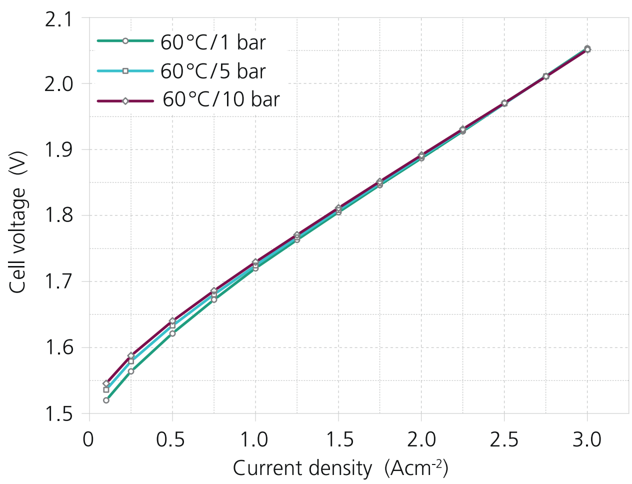
Progressive Cell Concepts for the Large-Scale Mass Production of PEM Electrolyzers

Innovative steps both in design and production are needed for PEM electrolyzer stacks to be produced competitively and in large numbers in Germany in future. At Fraunhofer ISE, we are intensively addressing different questions relating to the construction and production technology for PEM electrolysis.

For example, within the "CINES" project, a Fraunhofer Cluster of Excellence on Integrated Energy Systems, we have developed a progressive cell and stack design which addresses large-scale mass production of PEM electrolyzers. Based on previous development work, we have conceived a novel half-cell unit (HCU) as an essential component of a stack for PEM electrolysis, and produced a prototype with a cell area of 150 cm^2. We were able to operate this as part of a proof of concept with a current of up to 450 A.



Cell voltage versus current density at 60 °C for H_2 pressures of 1 bar, 5 bar and 10 bar.

The HCU unites the functionality of the individual components of conventional designs such as the frame, gasket, channel structures for provision of media and a porous transport layer within a single component – but without needing an additional frame component.

Many advantages result from using the presented HCU: Reduced costs for materials and production, fewer components – and thus simpler assembly – and new opportunities such as area upscaling, automated production processes and quality control of an HCU before assembly.

Already after the first project year, a preselection could be made of preferred design variants based on tests with a cell area of 4 cm^2. On that basis, we drafted, optimized, produced and successfully tested a design for an HCU with an area of 25 cm^2. Emphasis was placed here on reproducible quality in production and reliably high electrochemical performance. Finally, we were able to upscale the area to 150 cm^2. The proof of concept concluded successfully with electrochemical characterization of single cells and multi-cell assemblies. The measurement results demonstrate that in operation, the HCU is able to guarantee varying pressure and temperature loads at the anode and the cathode up to 10 bar and 80 °C without appreciable losses in performance.

Because of these positive results, a patent claim was filed for the developed design and production process. At present, we are working on upscaling to large cell areas of up to 600 cm^2 with higher hydrogen gas pressure, to achieve an industrially relevant version with comparable power density to that achieved in the proof of concept.

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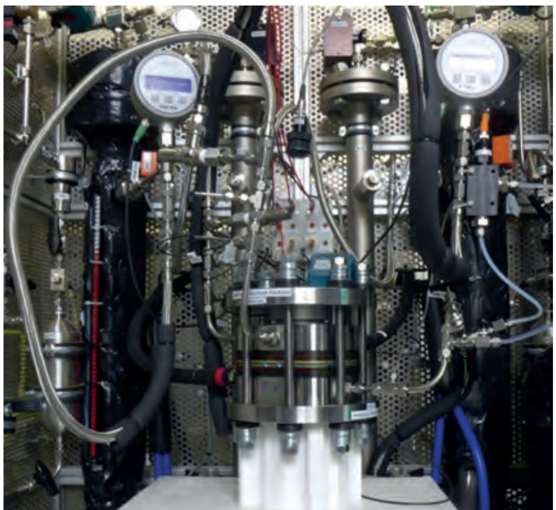
Assembled PEM electrolysis cell during electrochemical characterization.



Safety Tests for Batteries and Development of Solutions to Prevent Thermal Runaway

An essential feature of lithium-ion cells is their high energy density. Under unfavorable conditions, this is accompanied by the risk of thermal runaway. Risk factors include intrinsic cell defects, degradation and overheating, as well as failure or incorrect dimensioning of the battery management. As a result, very large amounts of heat and hot, in some cases toxic, gases can be released very quickly. The resulting pressure wave can have a destructive effect on neighboring cells and transform them into a critical state also. The phenomenon is then called "propagation".

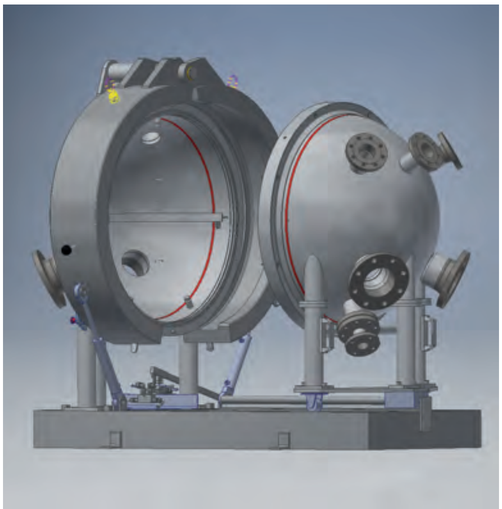
Within the "PLöPSS" project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), Fraunhofer ISE is researching the safety of lithium-ion batteries and is working on propagation-inhibiting solutions. Our goal is to develop propagation-inhibiting materials, flame-protective components and housing and to validate their properties. As part of the project, we have developed a hermetically sealed pressure tank with a volume of approximately 500 liters, a so-called propagation sphere. The test stand is designed for peak temperatures of up to 1 000 °C and a maximum pressure of 40 bar. Electric power cables to the test objects and data cables for the measurement technology are introduced via special bushings. The options to install numerous temperature and pressure sensors as well as the inertization allow the processes to be modeled accurately. Continuous video and infrared recording devices round off the equipment of the test stand.

In the Center for Electrical Energy Storage, we also test both according to standards and to client specifications. In particular, the validation of safety features and measures to prevent the propagation of fire are major aspects of our work. In addition, we have numerous bunkers which are equipped with the most modern measurement technology to determine temperatures and gas compositions. The laboratory is connected to a gas scrubber, which enables safe and emission-free conduction of experiments.

Press announcements about fires in battery storage units and electric vehicles show that there is still a need for research. Concretely, construction measures must reduce the probability of thermal runaway and propagation, the processes critical to safety must be retarded and – in the case of an accident – leakage outside the system housing must be prevented. To this purpose, we were able to reproduce the propagation processes between the cells in our propagation sphere and characterize new materials which retarded or prevented propagation. These investigations can also be transferred to new cell technologies and can make essential contributions to improving the safety of battery storage units decisively.

A battery cell is severely squeezed in a standardized test to mimic an accident.

CAD drawing of the propagation sphere.



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More Sustainability for Battery Cells and Concepts Along the Entire Value Chain

Battery storage units will play a major role in the future energy system. This makes it all the more important to investigate the sustainability of existing manufacturing processes and materials for batteries and improve this continually. At Fraunhofer ISE, we are addressing this question and have focused particularly on two aspects within the framework of current research projects: On the one hand, we are attempting to contribute to the established process of lithium-ion battery production with new, silicon-based materials. On the other hand, we are developing new battery chemistry and cell architectures, particularly for stationary applications.

Since January 2022, we have been working on commission to our industrial partner, the Duisburg investment holding company PCC SE, on the production of silicon-carbon composites in anodes for lithium-ion batteries within the "SICOM-LIB" project. Silicon features a specific capacity which is many times higher than that of the commonly used graphite, and can increase the energy density of lithium-ion batteries appreciably. It therefore allows the amount of material needed for anode production to be reduced. The silicon that we use is produced by PCC with green electricity, such that it is sustainable and climate-friendly. The silicon-carbon composites are conceived to be introduced successively into existing production lines as drop-in substitutes. As part of the project, an R&D pilot line to produce the silicon-carbon composites is to be constructed, so that the upscaling potential of the manufacturing process can also be investigated.

Within the "INFAB" joint project, which is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), we are working on sustainable battery concepts for stationary applications. Together with our industrial partners, Helmut Hechinger GmbH & Co. KG and acp system AG, as well as the University of Stuttgart, we are developing zink-based cell chemistry with suitable production processes, an appropriate battery cell architecture and the corresponding battery and energy management systems. Complementing the development of the cell architecture, the plan is to construct a pilot production line for the corresponding battery cells and take it into operation.

The targeted zink-based cell chemistry with an aqueous electrolyte opens up great opportunities with respect to a safe, sustainable, readily available and cost-effective battery technology. The electrolyte provides intrinsic safety and zinc is a readily accessible raw material with an established recycling route. Furthermore, within the project we have developed a novel electrode structure based on active charcoal, carbon black and polymer binders, which thus uses non-critical and also readily available raw materials. The electrode structure is produced without needing toxic solvents or complex drying processes. In addition, the electrode production process offers great flexibility for targeted design of the electrode properties and can also be used for other battery concepts, if required. Within the project, we also investigate the potential to use recycled material, particularly regarding carbon or the battery housing.

Electrode granulate as a precursor for the production of solvent-free electrode structures as part of battery cell development in the "INFAB" research project (material sample) and scalable electrode structure with adjustable properties with respect to porosity, electrode thickness and shape.

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Integration of Large Storage Units into Energy Systems

As the share of renewable energy sources in the electricity mix increases, so do the fluctuations in the generation of electricity. An essential challenge is to harmonize these with the energy demand profiles of consumers. Battery storage units provide a central element for the necessary restructuring of the electrical energy system, as they enable both technical and economic compensation for the fluctuations. Integrating them successfully into the electricity supply system is one of the research foci at Fraunhofer ISE.

Within the "Haid-Power" research project, which is funded by the State Ministry for the Economy, Labor and Tourism in Baden-Württemberg, we are cooperating with Fraunhofer EMI to embed a large storage unit into the new battery research center in the Haid industrial area of Freiburg. An energy management system (EMS) ensures that excess electricity from a photovoltaic plant is stored intermediately in the battery and is available later when there is insufficient solar radiation. In addition, the EMS is connected to a laboratory management system and can ensure that the connection power remains constant even when high-power test equipment and other laboratory facilities are operating simultaneously.

In addition to safety and reliability, the performance – determined by efficiency, effectivity and lifetime – is a decisive quantity for the economic viability of using energy storage units. Whereas small battery systems for domestic storage applications are already addressed by standards for safety and rules to determine the efficiency, such guidelines for the application of larger commercial and industrial (C&I) battery storage systems are still lacking. This is the motivation for the "AnLeiBat" project, which is financed by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), where the project partners, DKE, Fraunhofer ISE, StoREgio and VDE, are working on guidelines to evaluate the performance of C&I storage systems. They are intended to create a transparent basis for both providers and clients for the testing and quality control of battery storage systems and reliable, comparative evaluations. The work of Fraunhofer ISE is concentrating on bringing the knowledge which has been gathered over many years on battery storage, from the cell through the system up to the application, into the project, taking performance criteria into account.

PV array on the roof of the new center for electrical energy storage in the Haid industrial area of Freiburg.

By participating in these two and many further projects, we are continually extending theoretical and practical competence with regard to large storage units. By cooperating with research institutions and industrial enterprises, we make an important contribution to their successful integration into the energy supply system.

Manual measurement of an energy storage system at Fraunhofer ISE.

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Events in 2023 with Participation of Fraunhofer ISE

January

Abu Dhabi Sustainability Week	Abu Dhabi, United Arab Emirates	19. – 25.01.2023
Batterieforum Deutschland	Berlin, Germany	18. – 20.01.2023
SPIE Photonics West	San Francisco, USA	31.01. – 02.02.2023

February

PVinMotion	's-Hertogenbosch, Netherlands / hybrid	15. – 17.02.2023
World Hydrogen MENA	Dubai, United Arab Emirates	27.02. – 02.03.2023
38. PV-Symposium	Kloster Banz, Bad Staffelstein, Germany	28.02. – 02.03.2023

March

International Battery Seminar	Orlando, USA	20. – 23.03.2023
Volta-X	Stuttgart, Germany	28. – 30.03.2023

April

Silicon PV	Delft, Netherlands / hybrid	11. – 13.04.2023
AgriVoltaics2023	Daegu, South Korea	12. – 14.04.2023
Hannover Messe	Hanover, Germany	17. – 21.04.2023
BAU	Munich, Germany	17. – 22.04.2023
OWPT Conference	Yokohama, Japan	18. – 21.04.2023

May

Berliner ENERGIETAGE	online	03. – 05.05.2023
	Berlin, Germany	22. – 23.05.2023
Metallization and Interconnection Workshop	Neuchâtel, Switzerland	08. – 09.05.2023
33. Solarthermie-Symposium	Bad Staffelstein, Germany	09. – 11.05.2023
PCIM	Nuremberg, Germany	09. – 11.05.2023
IEA Heat Pump Conference	Chicago, USA	15. – 18.05.2023
e-world Energy & Water	Essen, Germany	23. – 25.05.2023
The Battery Show Europe	Stuttgart, Germany	23. – 25.05.2023
SNEC PV Power Expo	Shanghai, China	24. – 26.05.2023
EMRS Spring Meeting	Strasbourg, France	29.05. – 02.06.2023

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

June

tandemPV Workshop	Chambery, France	06. – 08.06.2023
IEEE Photovoltaic Specialists Conference	San Juan, Puerto Rico	11. – 16.06.2023
HOPV23	London, United Kingdom	12. – 14.06.2023
International Energy Workshop	Golden, Colorado, USA	13. – 15.06.2023
Intersolar / The Smarter E	Munich, Germany	14. – 16.06.2023
LASER World of Photonics	Munich, Germany	27. – 30.06.2023

September

IAA Mobility	Munich, Germany	05. – 10.09.2023
EUMETSAT Meteorological Satellite Conference 2023	Malmö, Sweden	11. – 15.09.2023
hy-fcell	Stuttgart, Germany	13. – 14.09.2023
CISBAT 23	Lausanne, Switzerland	13. – 15.09.2023
PSCO-23	Oxford, United Kingdom	18. – 20.09.2023
EU PVSEC	Lisbon, Portugal	18. – 22.09.2022
NUFAM Nutzfahrzeuge	Karlsruhe, Germany	21. – 24.09.2023

October

SolarPACES 2023	Sydney, Australia	10. – 13.10.2023
World Hydrogen Energy Summit 2023	Neu-Delhi, India	16. – 17.10.2023
Cemove360 Europe	Munich, Germany	17.10.2023
European Heat Pump Summit	Nuremberg, Germany	24. – 25.10.2023

November

PVSEC-34	Shenzhen, China	06. – 10.11.2023
Productronica	Munich, Germany	14. – 17.11.2023
PVM Modultechnologie und Effizienzworkshop	Freiburg, Germany	16.11.2023
DKV Tagung	Hanover, Germany	22. – 24.11.2023
MRS Fall Meeting & Exhibit	Boston, USA	26.11. – 01.12.2023
DecarbXpo 2023	Düsseldorf, Germany	28. – 30.11.2023

December

Hydrogen Dialogue	Nuremberg, Germany	06. – 07.12.2023

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