Fraunhofer ISE

Fraunhofer Institute for Solar Energy Systems ISE

R&D for the Energy Transition

Annual Report 2023/24

The cover illustration shows a detail of an InCellPlate® electro-plating facility to metallize silicon wafers. In this process, local metal contacts of electrically conductive copper are deposited onto the raw wafers in an electrolyte bath.

The use of electro-plated copper instead of the commercially widespread, printed silver contacts on silicon solar cells was developed at Fraunhofer ISE and will now be industrialized by PV2+, a new spin-off company originating from the Institute. The technology offers essential benefits – for instance, cost advantages can be expected for solar cells with copper contacts. In addition, copper is readily available in Germany and easily recycled. This allows solar cell production to become more sustainable.

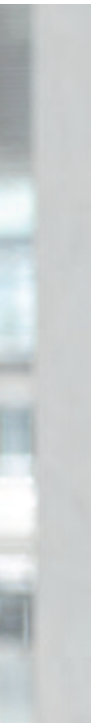
Results and Figures

Annual Report 2023/24

Foreword

Recent years have revealed the vulnerability of the European energy supply. Alongside the goal of climate neutrality, the demand for increased resilience will thus be stronger in future. More than 40 years ago, Fraunhofer ISE had already begun to address the increasingly urgent questions relating to a sustainable energy supply. One person, who recognized many of these questions well in advance and who laid the basis for successful work at the Institute with his own contributions, passed away last year – Prof. Adolf Goetzberger, the founding Director of Fraunhofer ISE, died on 24th February, 2023 at the age of 94. We remember the visionary work of Adolf Goetzberger with great respect and gratitude und humbly honor his lifelong scientific achievements and untiring efforts for research on solar energy systems.

His activity is simultaneously an example and a stimulus to develop the research fields at the Institute further, continually and consistently, so that important contributions toward successful implementation of the energy transition can also be delivered in future. So that we can react better to the growing demand for systemic solutions, we have redesigned the internal structure of Fraunhofer ISE and grouped relevant competences more closely together. Since July 2023, the Institute is organized in four Divisions, Photovoltaics, Power Solutions, Heat and Buildings, and Hydrogen Technologies. In addition, we have established the program line "Overarching System Integration" to react to the increasing demand for comprehensive, complete solutions for resilient and ultimately climate-neutral energy supply to industrial real estate and neighborhoods.



At the end of September, we were very pleased to have the opportunity to greet the new President of the Fraunhofer-Gesellschaft, Prof. Holger Hanselka, in Freiburg. Prof. Hanselka assumed office with the goal of advancing the mission of the Fraunhofer-Gesellschaft to reinforce the economy and further strengthen its position as an essential supplier of innovation to small, medium-sized and large enterprises. Cooperation with industry is also our focus at Fraunhofer ISE: Our activities will be directed toward eight new, market-oriented Business Areas from 2024 onward.

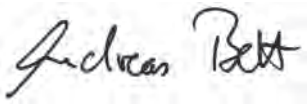
In the field of photovoltaics, we are promoting the re-establishment of a PV industry in Europe. We are supporting the industry here with feasibility and economic viability analyses, but also by developing the next generation of photovoltaics on the basis of multi-junction solar cells. The establishment of a European solar economy is also being pursued with high priority in Germany, and research and industry need rapid governmental support in this process. At the invitation of Fraunhofer ISE, around one hundred actors in the photovoltaic branch gathered at Fraunhofer ENIQ in Berlin in July to discuss possible cooperation for new PV production facilities in Germany. The focus of our research work for the solar industry continues to be the development of new cells, components and modules, and quality assurance in applications. To test and measure PV modules, we officially opened our outdoor test field in Merdingen near Freiburg in May, allowing us to combine laboratory measurements with outdoor analyses.

In 2023, the building sector was very much at the center of public attention and heat pumps were widely discussed. We continue to conduct intensive research on improving heat pumps, particularly concerning the application of natural refrigerants such as propane. In close cooperation with manufacturers and the housing sector, we are developing heat pump systems for existing apartment buildings and scientifically accompany demonstration projects and field tests. The revised version of the German building energy law (GEG), which was adopted in 2023 after vehement public discussion, ushers in the changeover to heating with renewable energy sources. We see this as an incentive to proceed with developing practicable solutions for a successful heating transition and to make heat pump technology more cost-effective and yet more widely applicable.

We were particularly pleased about the prizes and awards which members of the Institute staff received this year for their scientific work. We would like to highlight the Hertha-Sponer Prize, with which the Deutsche Physikalische Gesellschaft recognized Dr. Juliane Borchert for her work on new solar cell materials and the Research Prize of the Werner Siemens Foundation (WSS) accompanied by prize money of one million euros, which was awarded to Dr. Frank Dimroth and one of the Institute Directors, Prof. Andreas Bett. We heartily congratulate Dr. Ralf Preu for his successful post-doctoral treatise on the topic of PERC technology for solar cells, Prof. Sonia Dsoke on her appointment to the Chair for "Electrochemical Energy Carrier and Storage Systems" and Prof. Holger Neuhaus on his appointment to the Chair for "Material Systems for Solar Energy Use". Both professorships are at the Department of Sustainable Systems Engineering (INATECH) in the Faculty of Engineering of the University of Freiburg and are associated with work at Fraunhofer ISE. Similarly, we congratulate Dr. Peter Schossig on his appointment to the Chair for "Technologies for Climate-Appropriate Buildings and Neighborhoods" at the Karlsruhe Institute of Technology (KIT). This professorship, which will start on 1st April, 2024, is also combined with work at Fraunhofer ISE.

The conversion of our global energy system to include large shares of energy from renewable sources will be successful only if all requirements on sustainability are met. We have thus incorporated the topic of sustainability as a core element into our Institute strategy. We intend to include sustainability questions consistently both from the beginning of our research and development work and also by successively transforming our Institute's operation to become climate-neutral. An important step in this direction was the certification for energy management according to the DIN EN ISO 50001:2018 standard, which was achieved in September. As one of the first Fraunhofer Institutes to be certified according to this standard, we simultaneously prepared a template which should significantly accelerate the certification process for further Fraunhofer Institutes.

We extend our sincere gratitude to our Board of Trustees, industrial partners, scholarship donors, and funding agents in the Ministries at the Federal and State levels, as well as our project partners, for their trust in our work as well as their support and funding of Fraunhofer ISE. We are very much looking forward to further cooperation.



Prof. Hans-Martin Henning

Prof. Andreas Bett

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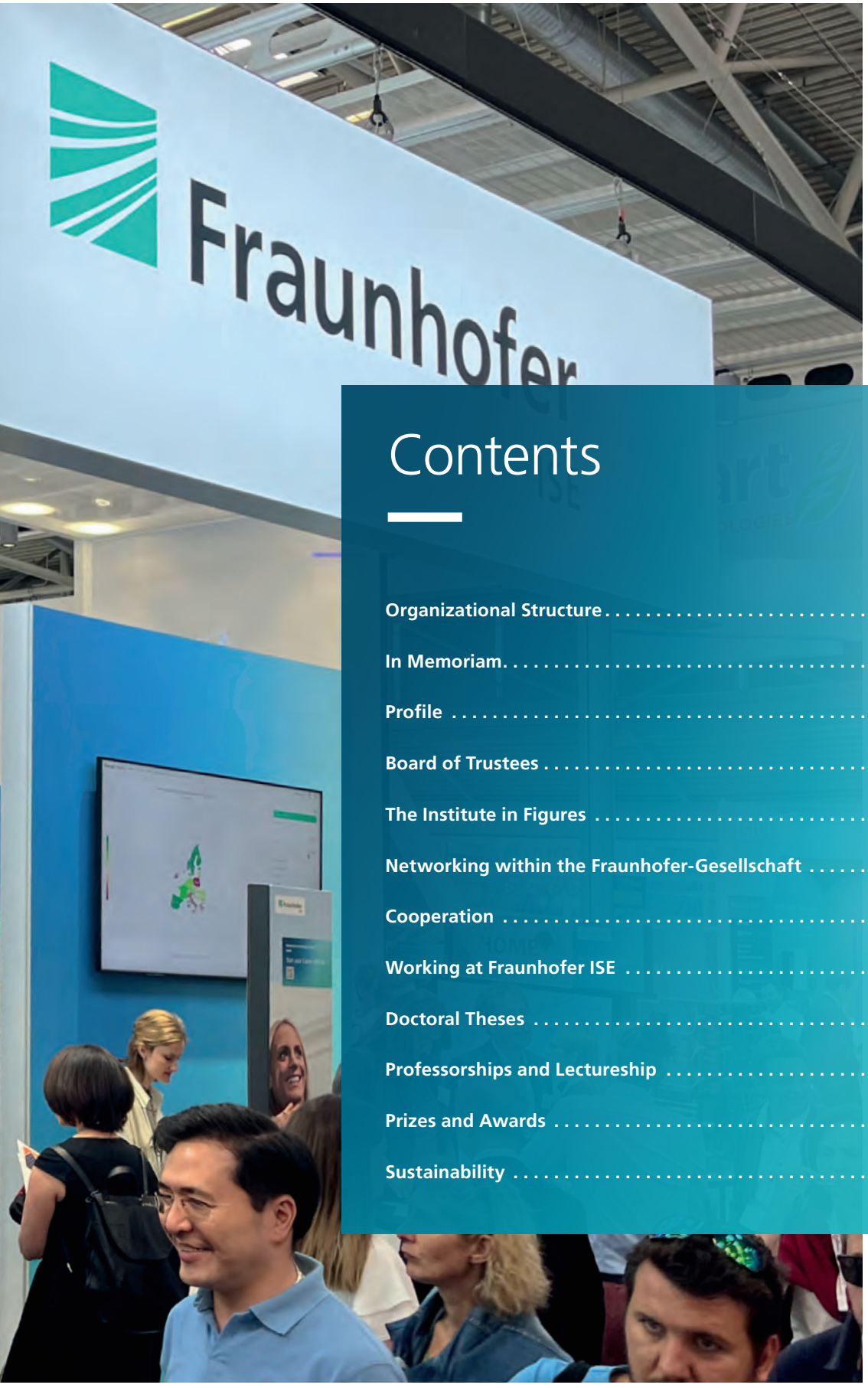
Our newsletters offer regular updates on our research highlights.

Facts and Figures



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Organizational Structure








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

Fraunhofer ISE is structured, apart from administrative and staff units, into four large scientific Divisions: Photovoltaics, Power Solutions, Heat and Buildings, and Hydrogen Technologies. In addition, the Institute has established the program line "Overarching System Integration".

We operate in eight market-oriented business areas for external representation:

- Photovoltaics: Materials, Cells and Modules
- Photovoltaics: Production Technology and Transfer
- Solar Power Plants and Integrated Photovoltaics
- Power Electronics and Grids
- Electrical Energy Storage
- Climate-Neutral Heat and Buildings
- Hydrogen Technologies
- System Integration

Fraunhofer ISE is supported by long-standing mentors and experienced experts in the solar energy sector:

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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Dr. Achim Schaadt
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Program Line: Overarching System Integration
Prof. Christof Wittwer
Phone +49 761 4588-5115

In Memoriam

The solar pioneer and founder of the Fraunhofer Institute for Solar Energy Systems ISE, Prof. Adolf Goetzberger, died on 24th February 2023, at the age of 94. With his death, Fraunhofer ISE has lost a greatly valued scientist and visionary prophet of solar energy, who supported the Institute with his advice to the end of his life.

It was against appreciable resistance that Adolf Goetzberger, then the Director of the Fraunhofer Institute for Applied Solid State Physics IAF, succeeded first in creating a dedicated working group on solar energy systems and then in establishing an independent Fraunhofer Institute Adolf Goetzberger led Fraunhofer ISE from its foundation until he reached retirement age in 1993. The Institute, in which the congruence of technology for solar energy and for energy systems was recognized and put into practice, grew rapidly to become one of the leading institutes for solar research and is the largest solar research institute in Europe today.

After studying experimental physics, Adolf Goetzberger completed his doctoral dissertation at the University of Munich on the crystallization of evaporated antimony layers in 1955. He subsequently worked together with the Nobel Prize winner and co-inventor of the transistor, William Shockley, in Californian Palo Alto and the famous Bell Laboratories in Murray Hill, New Jersey. In 1968 he returned to Germany and became the Director of the Fraunhofer Institute for Applied Solid State Physics IAF. In 1971, he was appointed as an honorary professor to the Faculty of Physics at the University of Freiburg and supervised many undergraduate and doctoral theses in this capacity.

"I was often asked how I came to focus specifically on solar energy, which was not taken seriously at all as an energy source at that time", wrote Adolf Goetzberger in 2018 in his memoirs. In particular, the study published by the Club of Rome in 1972 on "The Limits to Growth" had fascinated him. It seemed logical to him that we humans must use the sun as an inexhaustible source of energy, as the fossil fuel reserves were finite.

Adolf Goetzberger held more than 30 patents; the idea of agri-photovoltaics, which he already developed together with Dr. Armin Zastrow in 1981, is now experiencing its breakthrough. His participation and opinion were greatly appreciated in many evaluation committees, boards, commissions and

The solar pioneer and founder of Fraunhofer ISE, Prof. Adolf Goetzberger, died on 24th February, 2023, aged 94.

working groups. Just one example: Adolf Goetzberger was the President of the Deutsche Gesellschaft für Sonnenenergie DGS (German Society for Solar Energy) from 1993 to 1997.

The meritorious contributions of Adolf Goetzberger to the utilization of solar energy were recognized in many different ways: In 1983, Adolf Goetzberger was the first German to receive the J. J. Ebers Award of the American IEEE Electron Devices Society, for the development of the silicon field-effect transistor. He was honored with the Order of Merit of the State of Baden-Württemberg in 1989 and with the Order of Merit, First Class, of the Federal Republic of Germany in 1992. The International Solar Energy Society (ISES) presented him the Achievement through Action Award in 1993. In 1995, he received an honorary doctorate from the University of Uppsala and the Farrington Daniels Award of ISES. These were followed in 1997 by the Karl Boer Medal, the Becquerel Prize and the William R. Cherry Award. In 2006, the Solar World AG honored him with the Einstein Award and EUROSOLAR bestowed him with the European Solar Award. For his work throughout his lifetime, the European Patents Office recognized him with the European Inventor Prize in 2009.

The Directorate and all staff members of Fraunhofer ISE pay tribute to the lifelong achievements of Adolf Goetzberger. They are grateful for his successful efforts to develop solar energy systems and for his great resulting contribution toward a global energy transition.

Profile

Objective

The Fraunhofer Institute for Solar Energy Systems ISE is the largest solar energy research institute in Europe. Our staff of more than 1400 is committed to an energy supply system which is based on renewable energy sources and is sustainable, economic, secure and socially just. We contribute to this in our research focusing on energy supply, energy distribution, energy storage and energy utilization. We support the sustainable transformation of the energy system by excellent research results, successful industry projects, spin-off establishment and global cooperation. Fraunhofer ISE is financed by a combination of institutional funding and special programs of the Fraunhofer-Gesellschaft and other sources (17 percent). Around 62 percent of the total income is public funding (sources: German Federal Government, German States and EU), 21 percent originates from commissions from industry. The total budget of the Institute amounted to 135.3 million euros in 2023 (preliminary). Fraunhofer ISE is certified according to the quality management standard DIN EN ISO 9001:2015.

Research Approach

Our aspiration is to develop concretely implementable, technical solutions which we provide to our industrial partners or prepare jointly with them. 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 is all part of our work.

Fraunhofer ISE addresses eight market-oriented business areas (page 30 ff.). Our research approach ranges from materials research through component development up to systems integration. As systemic questions have become increasingly relevant in the context of the energy transition, Fraunhofer ISE established a new organizational structure in July 2023 to promote yet greater interdisciplinarity and interaction within its research (p. 26).

Services

Fraunhofer ISE is equipped with excellent technical infrastructure. A laboratory floor area of 22 300 m² – including a cleanroom area of 900 m² – and extremely modern equipment and facilities form the basis for our competence in research and development.

Our infrastructure of the highest technical standard encompasses eight R&D Centers and four production-relevant Technology Evaluation Centers (pages 46 ff.). Furthermore, the Institute offers testing and certification services in its test and calibration laboratories that are accredited according to DIN EN ISO 17025. On this basis, we operate as a reliable partner and implement R&D projects at the different levels of a technological lifecycle – exactly 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-based analysis/quality control
- Consultancy/planning / studies

Main building of Fraunhofer ISE.

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 2023. From left to right: Jürgen Heizmann, Pia von Ardenne, Dr. Stefan Reber, Burkhard Holder, Prof. Michael Bauer, Dr. Ingrid Vogler, Dr. Joachim Kloock, Peter Schneidewind, Dr. Norbert Schiedeck, Ullrich Bruchmann, Prof. Anke Weidlich, Sibylle Hepting-Hug, Thomas Speidel.

Chairman

Burkhard Holder
VDE Renewables GmbH, Alzenau

Members

Prof. Michael Bauer
Drees & Sommer SE, Stuttgart

Ullrich Bruchmann
German Federal Ministry for Economic Affairs and Climate Action (BMWK), Berlin

Dr. Gunter Erfurt
Meyer Burger AG

Jürgen Heizmann
JENOPTIK Optical Systems GmbH, Jena

Sibylle Hepting-Hug
Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg, Stuttgart

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Peter Schneidewind
RENA Technologies GmbH, Gütenbach

Prof. Armin Schnettler
Profas Energy Consult, Grünwald

Dr. Lioudmila Simon
E.ON Group Innovation, Essen

Thomas Speidel
ads-tec GmbH, Nürtingen

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

Dr. Ingrid Vogler
GdW Bundesverband deutscher Wohnungs- und Immobilienunternehmen e.V., Berlin

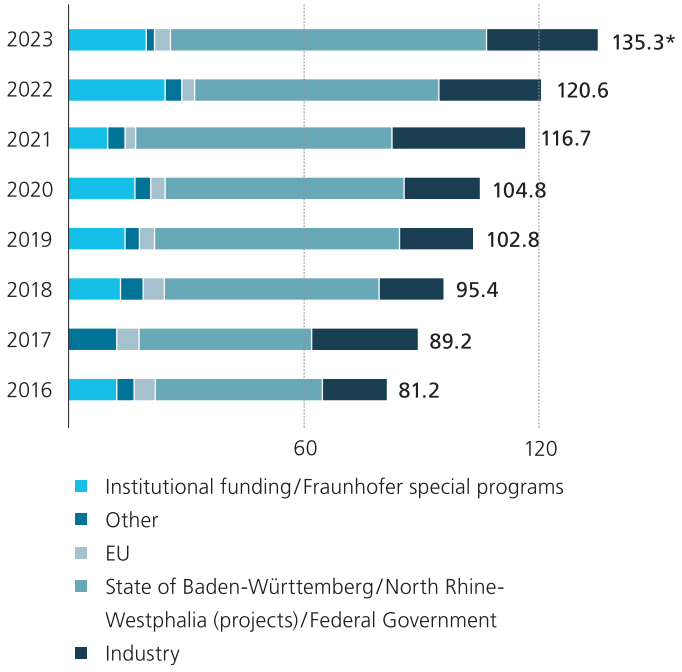
Prof. Anke Weidenkaff
Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS, Alzenau

Prof. Anke Weidlich
University of Freiburg

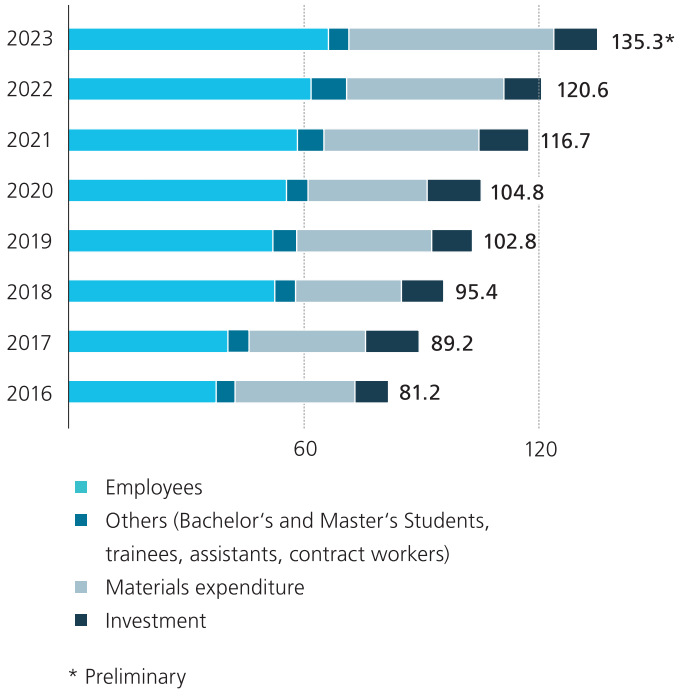
(Status: 31.12.2023)

The Institute in Figures

Income in Million Euros

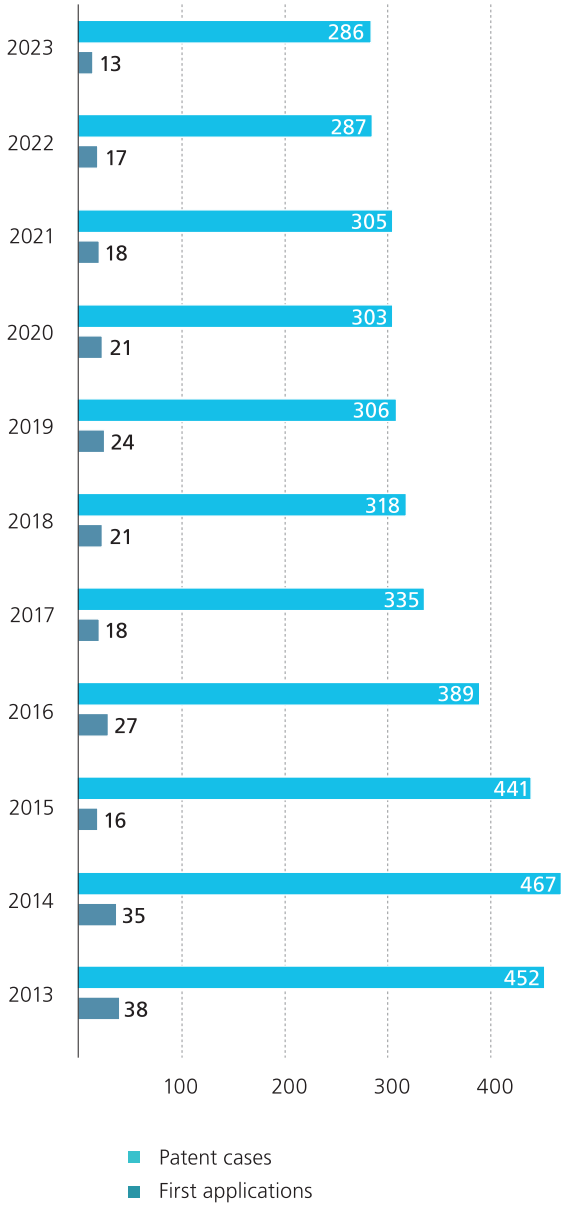


Expenditure in Million Euros

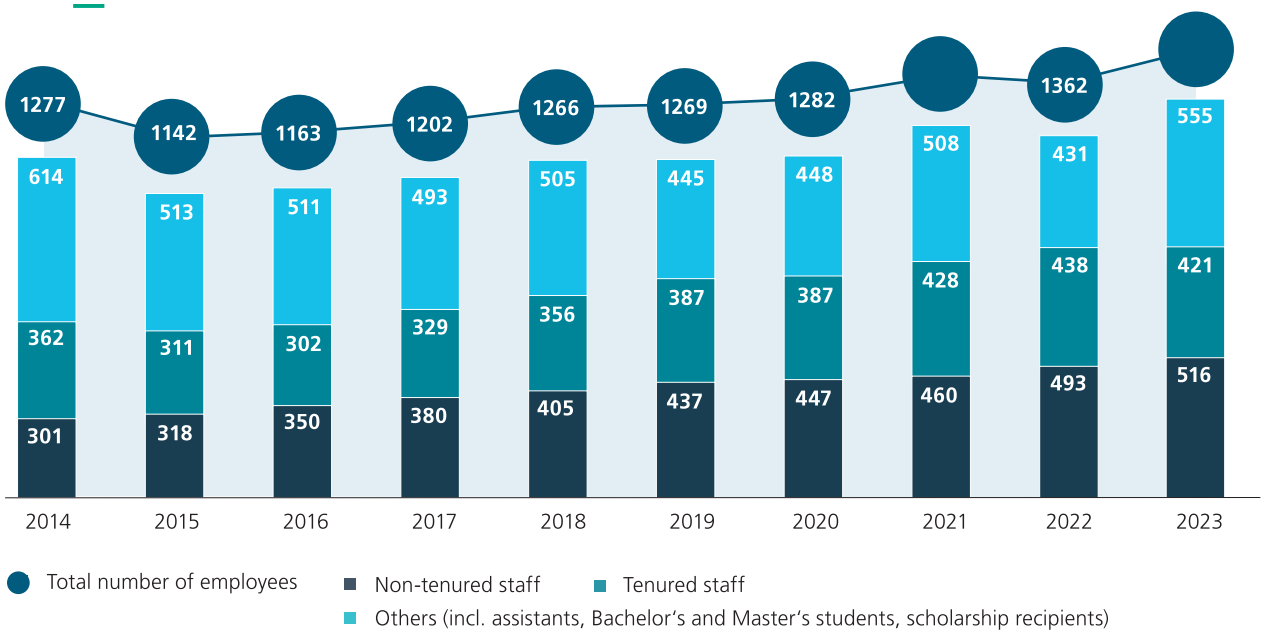


* Preliminary

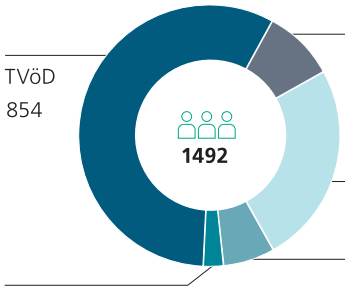
Patents



Personnel



Personnel in 2023



TVöD
854

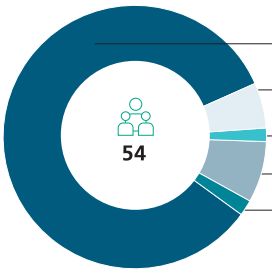
Diploma, Bachelor's and Master's students
136

Assistants
371

Doctoral students
97*
(* 83 are staff and 14 are scholarship recipients)

Apprentices, students (dual study program)
34

Lecture Courses and Seminars



University of Freiburg	45
KIT Karlsruhe Institute of Technolog	3
Ruhr University Bochum	1
Offenburg University of Applied Studies	4
TH Georg Agricola Bochum	1

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

Networking within the Fraunhofer-Gesellschaft

Fraunhofer ISE contributes a wide spectrum of competence to various associations and alliances by its networking within the Fraunhofer-Gesellschaft. 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 Technologies 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, Director of International Affairs 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 Lead Markets

Parallel to scientific excellence, transfer of results to the economic sector and society at large is also a focus of applications-oriented research. In this context, the Fraunhofer-Gesellschaft has defined nine lead markets which are addressed with high priority by the sector-oriented Fraunhofer Alliances.

Fraunhofer ISE is not only one of currently 19 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 Energy Renewable, Energy Storage, Energy Efficient, Energy Digital, Energy System, Energy Urban, Energy Grids, and Energy | Climate | Environment. Further networking within the Fraunhofer-Gesellschaft includes memberships in the Building Innovation and Aviation & Space Alliances, as well as in the Fraunhofer Cluster of Excellence on Integrated Energy Systems (CINES) and the Fraunhofer Networks for Sustainability and Hydrogen.

The Fraunhofer Energy Alliance presented itself with a joint booth at the trade fair E-world energy & water in Düsseldorf from 23rd to 25th May, 2023.

Cooperation

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

Cooperation with Universities

Fraunhofer ISE places great value on educating future scientists. Currently, 46 employees teach at universities; about 230 B.Sc., M.Sc. and Ph.D students work at the Institute. In addition, Fraunhofer ISE cooperates directly with numerous universities in Germany and around the world.

Cooperation with the University of Freiburg is particularly intensive. There is close collaboration with the Department of Sustainable Systems Engineering – INATECH within the Faculty of Engineering, 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 our expertise on photovoltaics to the livMatS Cluster of Excellence. For more than two decades, there has been close cooperation with the Freiburg Materials Research Center (FMF), where our activities on organic photovoltaics and battery research are located, for example. Similarly, we have a tradition of close cooperation with the Faculties of Physics, the Environment and Natural Resources, and Chemistry.

Among the courses which Fraunhofer ISE has initiated in cooperation with the University of Freiburg are the B.Sc. and M.Sc. courses on "Sustainable Systems Engineering" and the M.Sc. courses on "Renewable Energy Engineering and Management" and "Solar Energy Engineering".

Memoranda of Understanding

In addition, the Institute signed 16 Memoranda of Understanding with enterprises, organizations and research institutes around the world in 2023. The Institute is well connected at the national and the international levels within research and professional associations.

Students in Freiburg: Fraunhofer ISE has committed itself to educate future scientists by diverse forms of cooperation.

Working at Fraunhofer ISE

Since its foundation, Fraunhofer ISE has grown continually and is now one of the largest Institutes within the Fraunhofer-Gesellschaft. The relevance of our stated goal – a sustainable and socially just energy supply without fossil fuels – has also increased enormously in the public arena. This success is inconceivable without our excellent laboratory infrastructure but depends even more on the know-how, the commitment and creativity of our staff of more than 1400 – because science and its transfer into politics, industry and society depend on the people who are responsible for implementation. Selecting staff members for the Institute and encouraging them to stay there thus have high priority for us. It is with good reason that the Fraunhofer-Gesellschaft is among the most popular employers in Germany.

Shaping the Energy Transition Together

"Working at Fraunhofer ISE means more than just having a job", underlines Thomas Arnsberg, who heads Human Resources at the Institute. "It means doing something meaningful for the future every day. That applies equally well to the scientific employees as to those in administration. We are all acting in concert." The intention to work together toward a common goal is tangible: the positive and constructive way of cooperating at the Institute is endearingly called the "ISE spirit" by many insiders. Beyond this, the working culture and co-existence at Fraunhofer ISE is guided by values such as tolerance and equal opportunity – regardless of origin, religion, gender or age.

Multi-Facetted Tasks with a Perspective

Our staff members work on all facets of the energy transition. In our research Divisions for Photovoltaics, Power Solutions, Heat and Buildings, and Hydrogen Technologies, we offer attractive perspectives for young employees and doctoral candidates as well as for experts and managers with professional experience. At Fraunhofer ISE, we welcome not only scientists but also technicians, engineers and administrative experts. We also offer apprenticeships in IT, technical and commercial fields.

From Personal Development Programs to an Outdoor Terrace

A good work-life balance is increasingly important in the modern working world. We thus offer our staff members:

- Collegial and constructive cooperation
- Individual and flexible working hours with the option of home office
- Very modern workspace and laboratory infrastructure
- Rebates for childcare, holiday activities for schoolchildren, pme family service
- Hansefit, subsidy for a public transport ticket, retirement provision (VBL)
- Specific talent development via diverse personal development programs for different target groups
- Varied and healthy lunch from our canteen with a large outdoor terrace

We open doors to knowledge growth.

Change starts with us.

Strengthening the Position of Women in Science

It is our stated goal to strengthen the position of women in science. At present, about 22 percent of the scientific staff at Fraunhofer ISE consists of women. We aim to increase this share to 25 percent in 2025 and 30 percent in 2030. In addition, we are aiming to have 25 percent of managerial positions occupied by women in 2025 and 30 percent in 2030.

Among other initiatives, our professional development programs are contributing to this process. They are directed toward different target groups at different career levels. We already start with the undergraduate employees with the "ISE Young Talents" Program, which allows 40 students each year to discover the diverse research areas of Fraunhofer ISE with laboratory tours, networking events and expert lectures. The students are able to experience work beyond the sphere of their own working group and link up with other employees at the Institute. Beyond that, we accompany them in training courses and workshops in professional and personal development. At least 50 percent of the available places are allocated to women.

Further Professional Development Programs

- DokInCareer for female doctoral candidates
- Femovation for female scientists with their own project ideas
- TALENTA start, TALENTA speed up and TALENTA excellence for female scientists at three different stages of their careers

With the help of these programs, we make it feasible for the candidates to take time to write their doctoral theses or advance their career goals. Attendance at seminars and workshops on specific topics, as well as mentoring, promote personal and professional further development. At the same time, we support networking with other beneficiaries of programs like external scholarships at Fraunhofer ISE.

Shared knowledge: The library at Fraunhofer ISE offers comprehensive services to researchers and all members of staff.

Doctoral Theses

Sven Auerswald
"Dezentrale Fassaden-integrierte Wohnungslüftungsgeräte: kombinierte Bewertung des erzielten Luftaustausches und der Energieeffizienz" (Distributed façade-integrated apartment ventilators: Combined assessment of the achieved air exchange and energy efficiency), University of Freiburg, 2023

Varun Arya
"Laser Ablation of Dielectric Layers of Solar Cells", University of Freiburg, 2023

Oliver Fitz
"Entwicklung einer Zink-Ionen-Batteriezelltechnologie mit wässrigen Elektrolyten für stationäre Anwendungen" (Development of zinc-ion battery cell technology with aqueous electrolytes for stationary applications), University of Stuttgart, 2023

Sebastian Gamisch
"Untersuchung eines Thermomanagementsystems für stationäre Batteriespeicher basierend auf Phasenwechselmaterialien" (Investigation of a thermal management system for stationary battery storage based on phase-change materials), University of Freiburg, 2023

Gregor Gorbach
"Internal Carbon Pricing and its Use for the Decarbonisation in Organisations Considering Price Uncertainties", University of Freiburg, 2023

Arne Groß
"Stochastic Model Predictive Control for Smart Grid Applications", University of Freiburg, 2023

Katharina Gensowski
"Low-temperature Front-side Metallization for Solar Cell Applications Using a Parallel Dispensing Technology", University of Freiburg, 2023

Benjamin Hammann
"The Influence of Hydrogen on Silicon Solar Cells: Investigating the Link to Degradation Mechanisms", University of Freiburg, 2023

Lotta Koch
"Energy Performance and Ecological Potential of Solar Thermal Façade Collectors Made of Ultra-High-Performance Concrete (UHPC) for a CO_2 Neutral Heat Supply", Technical University of Munich, 2023

ISE Research School

The 2nd ISE DOK Colloquium took place on 24th October, 2023, in the Solar Info Center in Freiburg.

In April 2023, Fraunhofer ISE founded the ISE Research School. The graduate college has been created by the Institute to provide the best possible support to its doctoral candidates during their education and to encourage inter-departmental networking.

The program is open to all doctoral candidates at Fraunhofer ISE and encompasses the topics of research, teaching and interdisciplinary further education.

The ISE Research School offers a space for networking and interdisciplinary exchange: It provides the framework for the ISE DOK Colloquium, which takes place twice a year and is a platform for the doctoral candidates to present their work in the form of talks or posters. The program also includes lectures from renowned scientists: For example, the sustainability researcher, Prof. Arnim Wiek, held an invited lecture on 24th October, 2023, as part of the Colloquium.

As a longer-term perspective, Fraunhofer ISE expects that this structured program will further enhance the comprehensive education of doctoral candidates and increase the attractivity of the Institute for future doctoral research projects.

Franz Mantei
"Large-scale Production of Oxymethylene Dimethyl Ethers", Technical University of Berlin, 2023

Marius Meßmer
"Development and Characterization of Resource-Saving Doping Processes for Industrial Silicon Solar Cells", University of Freiburg, 2023

Jakob Metz
"Entwicklung und experimentelle Analyse eines Mehrquellen-Wärmepumpensystems aus Erdreich und Außenluft" (Development and experimental analysis of a heat pump system based on both ground and external air heat sources), University of Freiburg, 2023

Sebastian Roder
"Laserbasierte Wärmebehandlung zur Wirkungsgradstabilisierung und -steigerung von Solarzellen" (Laser-based thermal treatment to stabilize and improve the efficiency of solar cells), University of Freiburg, 2023

Stephan Schindele
"Nachhaltige Landnutzung dank Doppelernte. Eine mehrdimensionale Politikanalyse der Agri-Photovoltaik-Diffusion in Deutschland" (Sustainable land use thanks to a double harvest. A multi-dimensional political analysis of the dissemination of agri-photovoltaics in Germany), University of Tübingen, 2023

Patrick Schygulla
"III-V-Semiconductor Subcell Absorbers in Silicon-Based Triple-Junction Solar Cells", University of Freiburg, 2023

Charlotte Senkpiel
"Kopplung sozialwissenschaftlicher und individueller Aspekte mit Energiesystemmodellen: Theoretische Betrachtungen, Diffusion von Elektromobilität und Effekte regionaler Selbstversorgungsziele auf das Stromsystem" (Coupling of sociological and individual aspects with energy system models: Theoretical reflections, dissemination of electromobility and effect of regional supply autonomy goals on the electricity system), University of Freiburg, 2023

Maximilian Trommsdorff
"Techno-Economic Analyses of Agrivoltaics: Approaches in Arable Farming, Technology Choice, and Economic Performance in Horticulture", University of Freiburg, 2023

Jakob Ungerland
"Äquivalente dynamische Modellierung aktiver Verteilnetze mit netzfolgenden und netzbildenden Umrichtern" (Equivalent dynamic modeling of active distribution grids with grid-reactive and grid-forming inverters), University of Stuttgart, 2023

Natapon Wanapinit
"Characterization of Operational Flexibility Resources and Evaluation of Potential Utilization in Distributed Energy Systems", University of Freiburg, 2023

Zalma Zouhair
"Perovskite Photovoltaic Devices: Charge Selectivity of Carbon-Based Electrodes", Abdelmalek Essaadi University, Morocco, 2023

Professorships and Lectureship

Prof. Sonia Dsoke
W3 Chair for Electrochemical Energy Carriers and Storage Systems at the Institute for Sustainable Systems Engineering (INATECH), University of Freiburg, 2023

Prof. Holger Neuhaus
W3 Chair for Materials Systems for Solar Energy Use at the Faculty of Engineering, University of Freiburg, 2023

Dr. Ralf Preu
Post-doctoral treatise, Lecturer for Sustainable Technical Systems at the Faculty of Engineering, University of Freiburg, 2023

Dr. Peter Schossig
Appointment to the W3 Chair for Technologies for Climate-Appropriate Buildings and Neighborhoods at the Faculty for Architecture, Karlsruhe Institute of Technology, 2023

Prizes and Awards

Luis Eduardo Alanis
IEEE PVSC, Best Poster Award, "Analysis of Thermal Behavior and Reliability of Bare Die Diodes Embedded within PV Modules as Bypass Devices", IEEE PVSC Committee

Dr. Andreas Beinert
3rd Poster Prize, 38th PV-Symposium, "Bewertung von PV-Anlagen für Wind- und Schneelasten mit FEM-Simulationen" (Evaluation of PV systems for wind and snow loads with FEM simulations)

Prof. Andreas Bett, Dr. Frank Dimroth
Research Prize of the Werner Siemens Foundation (WSS), Finalists in the competition for the "Project of the Century"

Dr. Dmitry Bogachuk
Young Scientists' Prize, Doctoral thesis on "Understanding and Improving Perovskite Photovoltaic Devices with Carbon-based Back-Electrodes", Eva Mayr Stihl Stiftung

Dr. Juliane Borchert
Hertha Sponer Prize for research on new solar cell materials, German Physical Society (DPG)

Dr. Katharina Braig, Dr. Thibaud Hatt, Dr. Leonard Tutsch, Dr. Markus Glatthaar
Start-up BW Elevator Pitch 2023, Business Plan "PV2+", Start-up BW

Dr. Katharina Braig, Dr. Thibaud Hatt, Dr. Leonard Tutsch, Dr. Markus Glatthaar
Freiburg Innovation Prize 2023, Business Plan "PV2+", "Galvanikverfahren zum Ersatz von Silber durch Kupfer für Solarzellenkontakte" (Electro-plating process to replace silver by copper for solar cell contacts), Technologiestiftung BioMed Freiburg

Oliver Fischer
Student Award, "Spatially Resolved and Subcell-Selective Implied Open-Circuit Voltage Measurements on Perovskite Silicon Tandem Solar Cells", EU PVSEC 2023

Benjamin Hammann
SiliconPV Award 2023, Best Paper "Understanding the Firing Cooling Ramp's Influence on Light and Elevated-Temperature-Induced Degradation in Silicon"

Dr. Oliver Höhn
Consolidator Grant, research on highest-efficiency solar cells, European Research Council (ERC)

Dr. Florian Nestler
Peter and Luise Hager Prize 2023, Doctoral Thesis on "Dynamic Operation of Power-to-X Processes Demonstrated by Methanol Synthesis", Karlsruhe Institute for Technology

Paul Schlegel
2nd Prize of the Stiftung Energieinformatik in the category "Best M.Sc. Thesis", "Charakterisierung und techno-ökonomische Analyse von Verwertungspfaden für Sauerstoff als Nebenprodukt der Wasserelektrolyse", (Characterization and techno-economic analysis of utilization routes for oxygen as a by-product of aqueous electrolysis)

Paul Schlegel
Innovation Prize of the German Hydrogen and Fuel Cell Association (DWV) e.V. in the M.Sc. category for the thesis, "Charakterisierung und techno-ökonomische Analyse von Verwertungspfaden für Sauerstoff als Nebenprodukt der Wasserelektrolyse" (Characterization and techno-economic analysis of utilization routes for oxygen as a by-product of aqueous electrolysis)

Dr. Yam Siwakoti
Prizewinner of the Fraunhofer-Bessel Research Award of the Alexander von Humboldt Foundation

M.Sc. Prizes of the Verein zur Förderung der Solaren Energiesysteme e.V.

Johanna Aulich
M.Sc. thesis "Advanced IV Characterization Methods for Triple-Junction Solar Cells under Different Spectral Conditions"

Mohamed Mahmoud
M.Sc. thesis "Tuning Crystallization for Highly Efficient Monolithic Perovskite Silicon Tandem Solar Cells"

Anna Rothenhäusler
M.Sc. thesis "Control of Battery Systems in Industrial Companies with Reinforcement Learning"

Ella Susann Supik
M.Sc. thesis "Electrical and Optical Defect Characterization of Epitaxially Grown Silicon"

Nicolas Vollmar
M.Sc. thesis "Auslegung, Aufbau und Inbetriebnahme eines 100 kVA-Antriebsinverters für hybrid-elektrische Antriebssysteme in der Luftfahrt" (Design, construction and commissioning of a 100 kVA drive inverter for hybrid electric drive systems in aviation)

Sustainability

Fraunhofer ISE uses the electricity from Germany's first solar cycleway canopy. The system is located near the Institute and the Messe Freiburg (Freiburg Trade Exhibition site).

As pioneers of the transformation to a renewable and efficient energy supply, we at Fraunhofer ISE have a strong sense of obligation with regard to sustainability. Our Institute strategy is thus guided by the principle of comprehensive sustainability. For us, this means integrating sustainability, step by step, into our operation and the content of our work: into our research and development projects, into our management of human resources and building projects, as well as into operation and organization. To support this process, we continually set ourselves new goals and assess whether the measures taken were successful.

Research and Development

Major societal challenges such as the energy transition demand an interdisciplinary and often a transdisciplinary approach. We at Fraunhofer ISE are thus working in numerous research and development projects together with external partners on complete solutions for climate-neutral neighborhoods, municipalities and industrial real estate. To accompany these projects scientifically still better, we will strengthen our sustainability competences, create better links between internal and external interfaces and identify "blind spots" in R&D operation.

We position our work on solutions and decision bases for the energy transition in the context of the United Nations' Sustainable Development Goals. In the following chapters, our R&D projects with a specific focus on sustainability are identified by a symbol (from page 54).

Operation and Organization

Sustainability for the operation of our Institute particularly translates into saving energy and successively transforming the operation of our equipment and buildings to be more climate-friendly, with the ultimate goal of climate neutrality. During the past two years, we have implemented processes to reduce our consumption of gas and electricity, for example, by introducing energy-optimized processing sequences in our laboratories.

As an energy-intensive research institute, Fraunhofer ISE is currently developing a climate strategy, which includes a reduction of the externally supplied electricity by 25 percent until 2025 in comparison to the base year of 2019, among other aspects. We aim to reach this goal by a combination of reduced electricity consumption and on-site electricity generation. For example, we will expand the capacity of our photovoltaic systems by 2300 kWp and invest around 3.6 million euros to do so. We have introduced an energy management system to monitor all measures: in 2023, Fraunhofer ISE successfully absolved the relevant certification process according to DIN EN ISO 50001:2018.

Our commitment is in line with the strategy of the Fraunhofer-Gesellschaft. It is planning to make its research operation climate-neutral by 2045 and has created the "Fraunhofer klima-neutral" initiative to organize and implement the process. Along the path toward climate neutrality, the Fraunhofer-Gesellschaft aims to reduce its CO_2 emissions by 55 percent and compensate unavoidable emissions by 2030, as a first step. To this purpose, its own operational emissions will be determined, and savings potentials and areas for action identified.

Monitoring and Reporting

Fraunhofer ISE reports regularly on its sustainability activities and also publishes data and process information in its sustainability report, transparently and systematically according to the standards of the Global Reporting Initiative. Our successful participation in the Future Ranking of Sustainability Reports in 2021 that was organized by the German Institute for Ecological Economy Research (IÖW), as well as our nomination for the German Sustainability Prize in July 2023 in the "Education and Research" category, are incentives for us to continue the efforts we have started in the direction of comprehensive sustainability.

Strategy and Business Areas

Our newsletters offer regular updates on our research highlights.

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Strengthening German and European Industry Increases Resilience

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

Politics, the economy, media and society at large have all grappled intensively with the implementation of the energy transition during the past months. What effect did this have on the work of Fraunhofer ISE?

Bett: "Our Institute has been working for many years on technological solutions for the successful implementation of the energy transition. In that respect, it is positive for us when the topic is increasingly present in politics and public debate. The required technologies are fundamentally available but there are still challenges to industrial implementation. Politics and regulatory bodies are now confronted with the demanding task of setting the right boundary conditions."

Henning: "To be concrete, I would like to mention the topic of heat pumps, which we have been researching for many years, because we are convinced that this is a key technology for the decarbonization of the heating sector. The revision of the German building energy law meant that they were a major focus of attention last year. However, it became evident that it is not simple to introduce this type of technology, which basically functions well, to a broad market. Fraunhofer ISE can support the process by developing appropriate solutions that can be easily integrated into different applications such as in apartment buildings."

The corona pandemic, the "gas crisis" and the implementation of the energy transition all expose how strongly Germany depends on international suppliers. How critical is that?

Bett: "We have a certain degree of global dependence in almost all technologies, but a critical aspect is that this is increasingly focused on China. This is why the aspect of resilience in the technological sector is now so important as a basis for realizing the energy transition. We need to analyze exactly where components and products originate for each individual case. Can they be purchased in three or four countries on the global market or only one? The most prominent example is photovoltaics. 99 percent of the silicon wafers required for PV modules are manufactured in China. This means that a very critical dependence exists throughout the world, but it also offers a chance for establishing PV production in Europe. By contrast, when we look at heat pumps, there is indeed also a strong dependence on Asia for refrigerant compressors, but distributed over several countries in this case. For battery cells, where there is currently a strong dependence on China, important technological know-how still existed in Germany, and even more importantly, the political will to re-establish production again here in Germany. In building up production capacity, it is not always absolutely necessary to maintain distance from China; it is also possible to move forward together in cooperation."

Are there other technologies which should also be observed critically?

Henning: "At present, we must be particularly watchful concerning hydrogen. Here, we are still in an earlier phase of market development. The course must be set correctly now and know-how must be established in Germany and Europe to gain technological competence or even leadership, and avoid creating critical dependence. Great opportunities open up if the expansion is secured by flanking political measures. Technological development functions particularly well if it is used directly by local markets, such that application and upscaling can be implemented within the country. As a general principle, I find it important not to aim for autonomy. That cannot succeed, because even if the manufacturing technology is located here,

we are still dependent on delivery of raw materials. Thus, the topic of resilience should be viewed more broadly: Diversification of delivery sources and supply chains as well as technological sovereignty for key technologies. This means having access to important competences in Europe – not only in science but also in the economy – so that we can continue to act independently."

How can Fraunhofer ISE concretely support local industry in these efforts?

Bett: "Technologically, Fraunhofer ISE has driven developments forward in many areas and is at the global forefront. We draw on extensive experience. Now it is important to cooperate with industry to organize the transfer. That means that we can certainly support industry very well in answering current technological questions, but also to some extent in developing business models, and we can organize networking, which is very important if the goal is to build up major enterprises."

Henning: "We have also re-organized ourselves at the Institute, with the goal of implementing complete solutions yet more effectively and successfully. For example, the topics of PV power plants, power electronics and battery storage are now all gathered together into the newly created Power Solutions Division so that the key competences for the electricity transition can be combined at the technological level."

How can European manufacturers compete successfully on the international market, also with regard to the often lower prices in Asia?

Bett: "'Cheap production' often means that there is no price tag on factors such as CO_2 emissions and their effect on the climate or on social aspects such as humane working conditions, such that the true costs are not reflected. Awareness of these aspects must certainly still be more widely anchored in our society. At Fraunhofer ISE, we have decided to address the topic of sustainability holistically and strategically. Thus, we have intensified our efforts to study lifecycle analyses and all related dependences, which are indeed very complex. We are basing our research on this principle. In addition, we aim to develop technologies such that they are fit for a circular economy."

Henning: "Another aspect is that automation has not exhausted its potential. Our aspiration is to apply modern digitalization processes, including artificial intelligence methods, to the entire value chain, in order to access cost reduction potentials. A further important aspect is reducing the consumption of resources. We want to cooperate with industry in developing processes which require the smallest possible amounts of energy and materials and aim to re-use all components and materials completely – and this without increasing costs, if possible."

Are there further aspects which offer advantages for local industries?

Henning: "Advantages exist, for example, in integrated photovoltaics. Modules for these applications are produced in smaller series, which are optimized for the specific demands in buildings or in agriculture. Here, value will naturally be created primarily in the local region. It is also obvious that complete solutions for a specific location are usually best developed locally. One example is the development of climate neutrality for production sites. This is a direction which we aim to support specifically with our newly created cross-sectional topic of "System Integration" at the Institute. This can draw on all the competences that are distributed over the entire Institute, to develop customized solutions for commercial customers – for example, the housing sector or managers of industrial real estate."

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

Which concrete initiatives has Fraunhofer ISE planned for next year?

Bett: "It is still important for us to develop individual components further and to be at the forefront of technological development. But we want to offer more comprehensive, customer-oriented system solutions. We are well prepared for this as an Institute because we have such a broad base of competences. Beyond that, we can draw on our network within the Fraunhofer-Gesellschaft and with other research organizations. That is an aspect which our clients value highly. The sustainability goal will also be central for our R&D work. We thus see Fraunhofer ISE well prepared for the future."

New Organizational Structure and External Representation

The energy transition demands comprehensive restructuring of the energy supply, from its sources through distribution and storage up to utilization. For many decades, Fraunhofer ISE has participated in the technological development of key components for this conversion of the energy system, ranging from solutions for photovoltaics through grid technology and power electronics, electric and thermal energy storage, technology to generate and use hydrogen up to heat pumps. Technological further developments to improve performance and lower costs will continue to play an important role in future, whereby questions concerning sustainable production and efficient use of resources will become more significant. Sustainability is thus a core element of our Institute strategy. On the one hand, that means that sustainability aspects will be taken into account from the beginning of research and development work, and on the other hand, that the operation of our Institute itself will be continually developed further to reduce its effect on the climate and the environment.

As the level of technological development maturity increases, practical implementation is gaining enormously in importance for the success of the energy transition. For instance, political decisions have recently created the framework for restructuring the supply of heating in the building sector, which will lead to an accelerated implementation of new solutions. The further incorporation of renewable energy sources for electricity generation also has appreciable effects on electricity grids. Systemic solutions, including power electronics and storage at different grid levels are thus needed to guarantee a stable and reliable electricity supply in future. To meet these challenges optimally, we have adapted our organizational structure and created four large scientific Divisions:

- **Photovoltaics**
  (Leadership: Prof. Stefan Glunz, Dr. Ralf Preu)
- **Power Solutions**
  (Leadership: Dr. Harry Wirth)
- **Heat and Buildings**
  (Leadership: Dr. Peter Schossig)
- **Hydrogen Technologies**
  (Interim leadership: Ulf Groos, Dr. Achim Schaadt, Dr. Tom Smolinka, Robert Szolak)

In the Photovoltaics Division, cell and module development are now located under one roof. The grouping of photovoltaic power plants with power electronics, grid technology and battery storage technology in the Power Solutions Division strengthens our offer for systemic solutions for future supply of electricity. In the Heat and Buildings Division, we offer comprehensive solutions for the heating transition. The Hydrogen Technologies Division addresses the complete range of questions from the dynamically developing industry in this sector. This structure harmonizes excellently with the missions of "Electricity Transition", "Heating Transition" and "Hydrogen" propagated in the recently published, eighth energy research program of the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

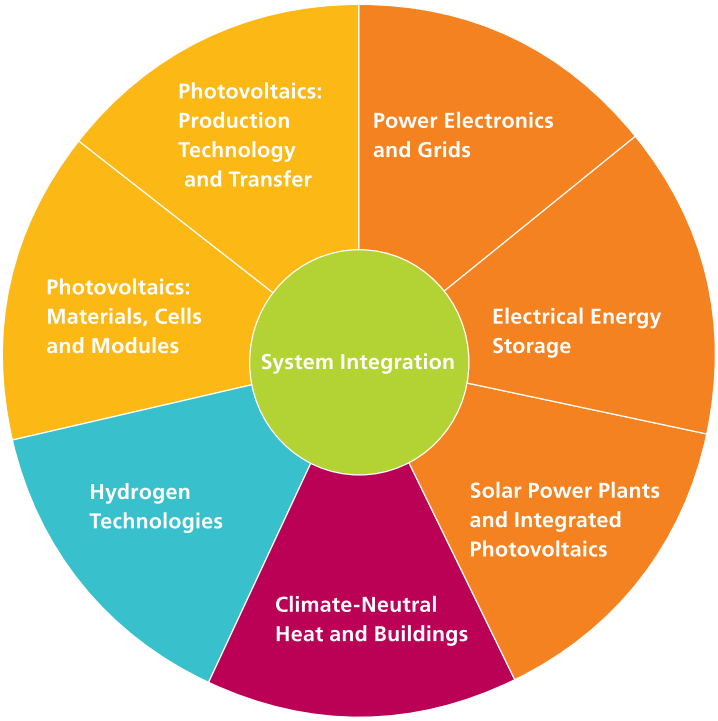
Fraunhofer ISE develops complete solutions for climate-neutral buildings, neighborhoods and municipalities. The photo shows the Gutleutmatten quarter in Freiburg, where distributed solar thermal systems were integrated into the local heating network.

In addition, we have developed a new structural element with the program line "Overarching System Integration", which will be led by Prof. Christof Wittwer. In this cross-sectional unit, comprehensive solutions for robust future energy supply systems will be researched, drawing on the know-how of the four more technologically oriented Divisions, and developed in cooperation with clients.

With this unit, we are reacting to the increasing demand from the economy and the public sector for complete solutions for climate-neutral buildings, neighborhoods, municipalities and industrial real estate, and will accompany implementation from concept development up to operation optimization, holistically and scientifically, in living laboratories and demonstration projects.

We have also reorganized our Business Area structure to achieve better customer orientation. This Annual Report is structured according to the eight new Business Areas, which form the basis of our external representation from 1st January, 2024:

- Photovoltaics – Materials, Cells and Modules
- Photovoltaics – Production Technology and Transfer
- Solar Power Plants and Integrated Photovoltaics
- Power Electronics and Grids
- Electrical Energy Storage
- Climate-Neutral Heat and Buildings
- Hydrogen Technologies
- System Integration



From 2024, Fraunhofer ISE is structuring its external representation according to eight new, market-oriented Business Areas.

Toward Resilient, European Photovoltaic Production

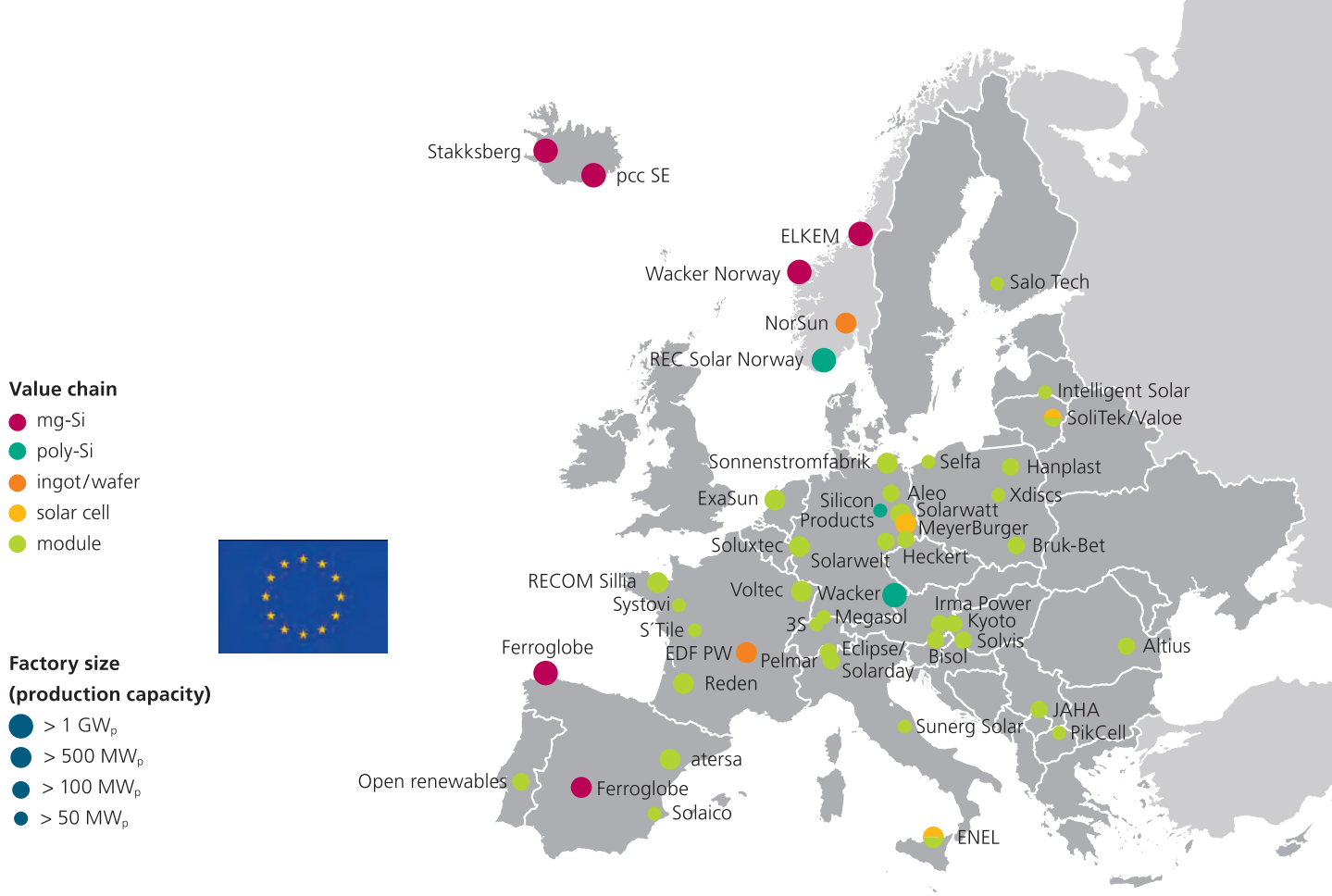
The European Commission stated the goal clearly in its "Net Zero Industry Act" (NZIA): In the photovoltaic sector, 40 percent of the capacity required in 2030 should be produced in Europe. Expansion of photovoltaic production is being promoted accordingly and the European solar industry is attempting to regain its former strength. At Fraunhofer ISE, we are accompanying this process with our expertise and are working closely with our industrial partners to strengthen existing production capacities and to establish new ones. For more than 20 years, we have supported European manufacturers of solar cells and modules with our know-how. In 2018, Fraunhofer ISE demanded retention of technological sovereignty in a White Paper. "In our view, it is necessary, also for reasons of self-reliance and political independence, to establish photovoltaic production and operate the complete value chain in European", summarizes one of the Institute Directors, Prof. Andreas Bett.

Creating Favorable Political Boundary Conditions

However, the boundary conditions are difficult, as China dominates both the PV market and the value chain for silicon photovoltaics, which accounts for more than 95 percent of the photovoltaic market. If this dependence is to be reduced, it is necessary to create political boundary conditions which allow fair competition. Thus, the European associations, the European Solar Manufacturing Council (ESMC) and Solar Power Europe (SPE) are jointly active within the ESIA Initiative (European Solar Photovoltaic Industry Alliance) in demanding European PV production along the value chain. Also, the German industrial association, Bundesverband Solarwirtschaft, has prepared a proposal: It proposes resilience bonuses as part of the German Renewable Energy Act (EEG) payments, which could be higher, depending on the share of European production.

Numerous measures will be needed to locate important technologies and production lines in Europe and thus build up greater resilience for the conversion of the energy system.

The Center for High Efficiency Solar Cells at Fraunhofer ISE in Freiburg.



Companies along the PV value chain in Europe.

Fraunhofer ISE – Partner for Industry

Fraunhofer ISE is already supporting manufacturers intensively now with R&D services and cooperates with businesses which are building up production capacity. For example, we will support the HoloSolis company with technology selection and factory planning during the conceptional design and building phase, on the basis of a strategic cooperation agreement that was signed in summer 2023. The company is planning to build a production line for PV solar cells and modules near the French-German border. Production is planned to start in 2025 and to produce five GW per year when operating at full capacity.

Furthermore, we are conducting research on a new generation of solar cells and developing module designs that will make Europe competitive. We support manufacturers of modules and production equipment in our well-equipped, modern production laboratory, Module-TEC, in which we can fabricate a wide variety of module sizes and designs and design each module individually. Together with the company, Heckert Solar GmbH, we have developed a PV module based on M12 half-cells with an efficiency of 20.5 percent. Fraunhofer ISE was responsible for the conception, preliminary development and the production of the first module prototypes.

The sustainability of production is particularly important to us at Fraunhofer ISE, i.e. we aim to reduce the energy consumption and make efficient use of raw materials. Success in re-establishing European photovoltaic production depends decisively on the availability of critical raw materials. Thus, we have anchored circular value creation as a goal in our Institute strategy. This encompasses the re-use of materials and components as well as feeding back into material cycles. Our goals are illustrated well by three spin-offs from the Institute: The NexWafe company addresses the market for high-quality wafers and has set itself the goal of upscaling the EpiWafer technology. The HighLine Technology GmbH enables resource-conserving application of pastes for cell metallization with its proprietary dispensing technology. The PV2+ start-up has commenced operation successfully with an electro-plating process to replace silver for solar cell contacts by copper.

Outlook

There are high expectations on the European Commission and the national German government to support the production of photovoltaics along the value chain. Fraunhofer ISE is accompanying this initiative and is thus expanding its capacity for module development in Module-TEC. At the end of February 2024, we will open our new production laboratory in the former Solarfabrik in Freiburg. Four million euros were invested in the site to establish existing and new production facilities for connection technology and lamination in a factory hall. This will allow us to support industrially relevant research on series production of solar modules still more efficiently and thus contribute to the establishment of resilient photovoltaic production in Europe.

Photovoltaics: Materials, Cells and Modules

Market Position

High conversion efficiencies and the resulting low levelized costs of photovoltaic electricity can only be achieved with optimal and cost-efficient materials. For silicon, organic, III-V and perovskite semiconductors, we achieve very good electronic properties by in-depth analyses and optimized processes. Based on these results, we apply simulation tools to optimize solar cell architectures and implement these in our laboratories. This leads to pathbreaking cell architectures such as the TOPCon silicon solar cell, which we developed and which has become established as an industrial standard throughout the world.

As the silicon solar cell is approaching its theoretical efficiency limit, we are developing the next solar cell generation on the basis of multiple-junction solar cells. In doing so, we apply our many years of experience with III-V semiconductors to produce promising tandem solar cells with new and potentially more cost-effective semiconductors such as perovskites. For module manufacturing, we are promoting new topologies such as matrix shingling which produces particularly aesthetically attractive results in combination with our MorphoColor® technology. In addition, we are conducting research on tandem modules, which enable the highest module efficiencies in fixed installations or in tracking systems with concentration.

Facts and Figures

Total staff	165
Journal articles and contributions to books	84
Lectures and conference papers	90
First patent applications	3

Leadership

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

Topics in this Business Area

Silicon Material and Semiconductor Substrates
Dr. Charlotte Weiss, Phone +49 761 4588-5591

Silicon Solar Cells and Modules
Dr. Ralf Preu, Phone +49 761 4588-5260

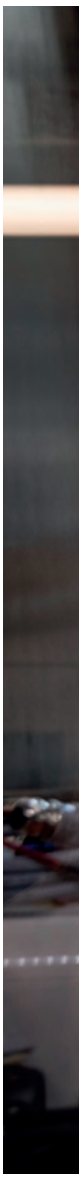
Silicon-Based Tandem Solar Cells and Modules
Dr. Martin Hermle, Phone +49 761 4588-5265

Perovskite Thin-Film Photovoltaics
Dr. Markus Kohlstädt, Phone +49 761 203-96796

Organic Photovoltaics
Dr. Uli Würfel, Phone +49 761 203-4796

III-V Solar Cells, Modules and Concentrator Photovoltaics
Dr. Frank Dimroth, Phone +49 761 4588-5258

Photonic and Electronic Power Devices
Dr. Henning Helmers, Phone +49 761 4588-5094



“We are opening the door to the next generation of photovoltaics with the development of perovskite-silicon multiple-junction solar cells.”

Maryam Heydarian and Mina Heydarian
Ph.D. candidates working on perovskite-silicon multiple-junction solar cells.

More Information

Business Area **Publications** **Projects**

Photovoltaics: Production Technology and Transfer

Market Position

Sustainable production of photovoltaic components requires comprehensive knowledge of their operating principles and manufacturing – this is where our expertise on production technology plays its role. The numerous production technologies currently in use include wet-chemical processes, epitaxial procedures to produce materials or laser and printing processes for solar cell manufacture. Coating processes are also applied for module production as well as connection and lamination technologies. The application of processing and characterization equipment must guarantee high performance, reproducibility and yield for the production of high-efficiency solar cells and modules.

In our large-scale laboratories, we develop innovative approaches from the proof of concept up to feasibility demonstrations in small series with well-established and novel production equipment. Our techno-economic and ecological approaches provide the basis for well-founded investment decisions for industrial manufacturers concerning e.g. the selection of photovoltaic components and the resulting necessary materials and equipment. These analyses also form the basis for our technology transfer to current and future manufacturers of photovoltaic components. Our experienced scientists and engineers support our partners hereby with services ranging from feasibility studies to production.

Facts and Figures

Total staff	313
Journal articles and contributions to books	84
Lectures and conference papers	90
First patent applications	2

Leadership

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

Topics in this Business Area

Material Technologies
Dr. Charlotte Weiss, Phone +49 761 4588-5591

Metrology and Simulation
Dr. Martin Schubert, Phone +49 761 4588-5660

Coating Technologies and High-Temperature Processes
Dr. Marc Hofmann, Phone +49 761 4588-5051

Wet and Dry Chemical Processes
Dr. Martin Zimmer, Phone +49 761 4588-5479

Laser and Printing Technologies
Dr. Jan Nekarda, Phone +49 761 4588-5563

Interconnection and Encapsulation Technologies
Prof. Holger Neuhaus, Phone +49 761 4588-5825

Artificial Intelligence and Data Management
Dr. Stefan Rein, Phone +49 761 4588-5271

Technology Assessment and Transfer
Dr. Jochen Rentsch, Phone +49 761 4588-5199

“Our extremely productive and mild laser processes enable the efficient application of widely available and cost-efficient materials in PV production.”

Jan Paschen and Anna Münzer
Ph.D. candidates working on laser-processing technology.

More Information

Business Area

Publications

Projects

Solar Power Plants and Integrated Photovoltaics

Market Position

We conduct research so that innovative, high-quality and cost-effective solar systems become established on all suitable surfaces. To this purpose, we develop methods and technologies for all aspects of PV modules and solar power plants and their applications. The integration of solar technology into the urban space, into transport infrastructure and on agricultural and water-covered areas exploits an enormous additional potential area. Due to the large share of energy from renewable sources, solar performance prediction is becoming increasingly important. We are thus developing prediction models for reliable forecasts, depending on the PV usage duration and the area occupied by PV.

We guarantee comprehensive quality assurance, following the phases of Fraunhofer ISE's quality cycle – Development, Engineering, Procurement, Commissioning und Operation. With our simulation tools, we investigate the potential and feasibility of new technologies, taking site-specific and climatic factors into account. Our team characterizes the performance of new module technologies and tests their reliability in the laboratory and in the field. Our services also cover solar-thermal power stations and their combination with photovoltaics and power-to-X technologies.

Facts and Figures

Total staff	145
Journal articles and contributions to books	22
Lectures and conference papers	64

Leadership

Dr. Anna Heimsath, Phone +49 761 4588-5944

Topics in this Business Area

Module Analysis and Reliability
Daniel Philipp, Phone +49 761 4588-5414

Photovoltaic Solar Power Plants
Dr. Anna Heimsath, Phone +49 761 4588-5944

Integrated Photovoltaics
Dr. Harry Wirth, Phone +49 761 4588-5858

Solar Thermal Power Plants
Dr. Gregor Bern, Phone +49 761 4588-5906

Solar Energy Meteorology
Dr. Elke Lorenz, Phone +49 761 4588-5015

Double usage of land areas offers manifold options to agriculture, industry and municipalities for local electricity generation.”

Dr. Anna Heimsath, Business Area Leader for Solar Power Plants and Integrated Photovoltaics, and **Oliver Hörnle,** project leader for agri-photovoltaics.

More Information

Business Area

Publications

Projects

Power Electronics and Grids

Market Position

The integration of renewable energy into our energy system is increasing – and thereby the electrification of energy supply in the electricity, heat and mobility sectors. Along the pathway from generation to final use, electricity passes through numerous power-electronic conversion steps. As a result, the expansion of renewable energy is accompanied by the dissemination of electricity inverters and digital systems in all market segments.

With the help of the most modern components and technologies – e.g. on the basis of SiC and GaN semiconductors – essential advantages can be realized at the system level. These are urgently needed to reach the goals set for the energy transition with the available and exploitable raw material resources. Interoperability, digitalization and modeling of energy systems is also becoming increasingly important. In a decentrally organized electricity grid without conventional power plants, inverters will be responsible for system stability in future. However, also the extension of loads with grid-supportive functions and energy management will play a greater role. We support our industrial partners on these topics both with our expertise and also with our infrastructure in the "Center for Power Electronics and Sustainable Grids".

Facts and Figures

Total staff	102
Journal articles and contributions to books	5
Lectures and conference papers	24

Leadership

Christian Schöner, Phone +49 761 4588-2078

Topics in this Business Area

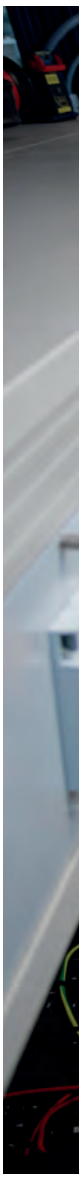
Power Converters
Stefan Reichert, Phone +49 761 4588-5476

High-Power Electronics and System Engineering
Andreas Hensel, Phone +49 761 4588-5842

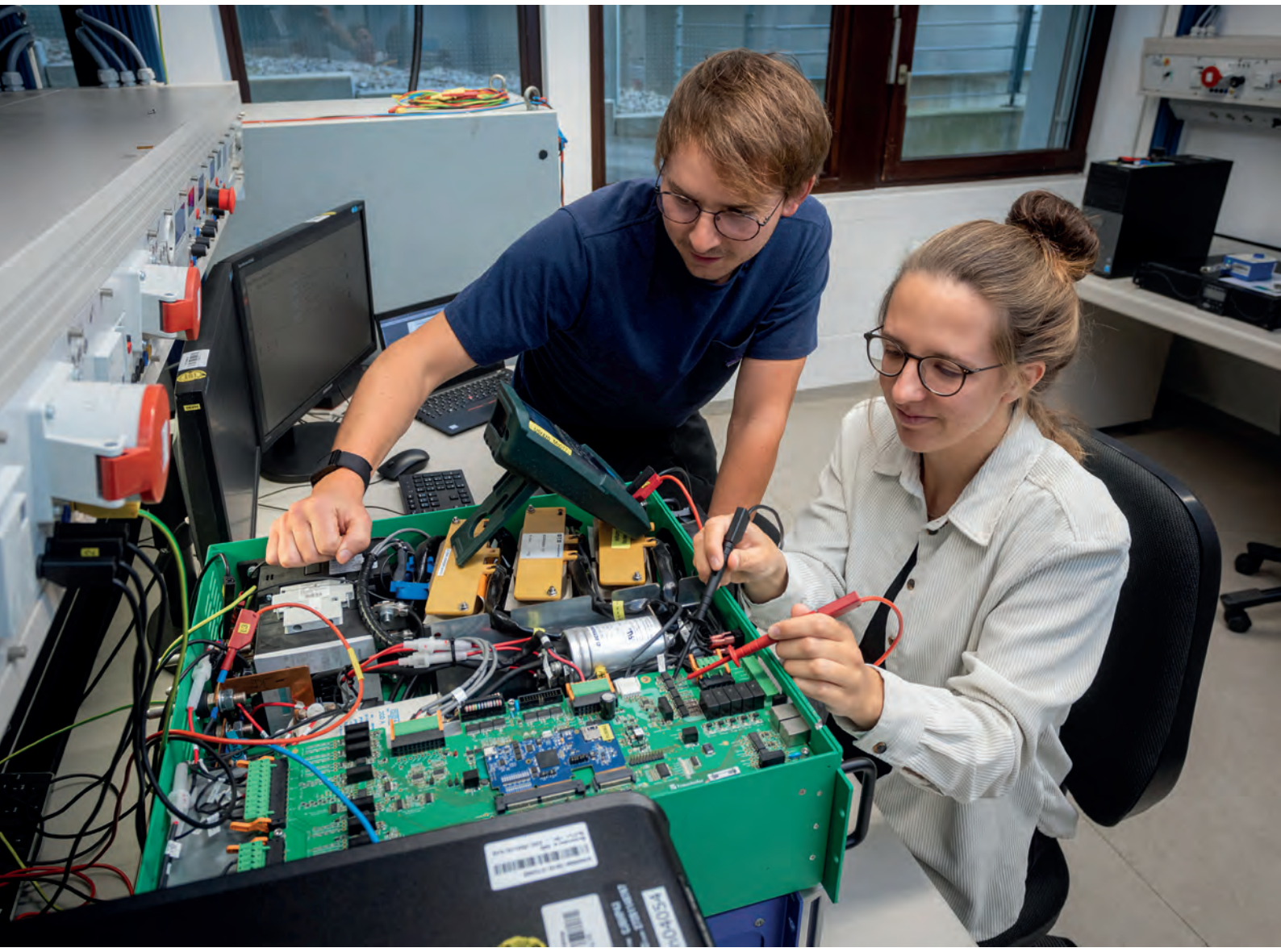
Smart Metering and Grid Control
Marco Mittelsdorf, Phone +49 761 4588-5446

Grid Planning and Operation
Dr. Bernd Wille-Haußmann, Phone +49 761 4588-5443

Converter-Based Power Grids and System Stability
Roland Singer, Phone +49 761 4588-5948



“We conduct research on important key technologies for successful sector coupling.”



Philipp Ernst, manager of the Verbundnetz Stabil project, and **Franziska Hans,** scientist.

More Information

Business Area

Publications

Projects

Electrical Energy Storage

Market Position

The energy transition and a sustainable transformation of the mobility sector can succeed only with the help of safe, reliable and high-performance battery storage units. The demand for corresponding battery technologies will thus increase exponentially. To achieve the stated goals, a sustainable circular economy will also be needed, as is addressed in the European Battery Regulation. Digitalization plays a central role within this context in the production, utilization phase and end-of-life (EOL) areas.

The specifications on battery management systems that are defined as part of the battery passport – e.g. concerning transparency about the state and remaining lifetime – are also drivers of this development.

In our "Center for Electrical Energy Storage", we are researching the next generation of lithium-ion batteries and promising alternatives such as zinc-ion or sodium-ion technologies. We view the entire value chain – from materials and cells through battery systems technology up to diverse storage applications. The laboratory infrastructure in the Haidhaus in Freiburg allows us to offer extensive scientific tests at the cell and system levels, as well as modern characterization procedures.

Facts and Figures

Total staff	88
Journal articles and contributions to books	4
Lectures and conference papers	26
First patent applications	2

Leadership

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

Topics in this Business Area

Battery Management and Cells
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Battery Engineering
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Production Technology for Batteries
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Battery Integration and Operational Management
Nils Reiners, Phone +49 761 4588-5281

Technology Evaluation for Batteries
Manuel Bergmann, Phone +49 761 4588-2818

“Batteries are a central key to a sustainable and reliable electricity supply.”

Dr. Moritz Kroll, deputy leader of the “Battery Testing Lab”, and **Dr. Lea Eisele,** leader of the Battery Cell Technology group.

More Information

Business Area

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Projects

Climate-Neutral Heat and Buildings

Market Position

The changeover to renewable energy carriers is becoming increasingly urgent, not only to protect the climate but also to ensure supply and price stability. In the building sector, the specific challenge is to provide technical and systemic solutions which address a wide bandwidth of actors. Possible solutions include technology for non-fossil heat generation, transformation concepts for the housing sector, industry and commerce, and heat supply, as well optimization of the processes by digitalization. In the construction sector, productivity can be raised only by standardization and digitalization of the building processes, such as the standardized PV modules that we are developing for façade integration.

In order that an accelerated uptake of heat pumps with natural refrigerants can succeed in the building sector, we are technologically supporting the development of optimized refrigerant circuits and ensure quality by laboratory and field tests. We also develop cooling circuits and exploit new heat sources to enable increased utilization of large and high-temperature heat pumps for heating networks and industrial applications. Furthermore, we work on integration of the equipment into each specific application.

Facts and Figures

Total staff	221
Journal articles and contributions to books	29
Lectures and conference papers	37
First patent applications	1

Leadership

Sebastian Herkel, Phone +49 761 4588-5117

Topics in this Business Area

Building System Technology
Dr. Peter Engelmann, Phone +49 761 4588-5129

Operational Management for Buildings, Properties and Industry
Nicolas Réhault, Phone +49 761 4588-5352

Building Envelopes
Dr. Bruno Bueno, Phone +49 761 4588-5377

Heat Pumps
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Hot and Cold Storage
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Ventilation, Air-Conditioning, Refrigeration
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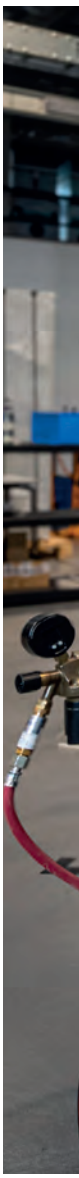
Water Treatment and Materials Separation
Dr. Joachim Koschikowski, Phone +49 761 4588-5294

Solar Thermal: Systems and Components
Dr. Korbinian Kramer, Phone +49 761 4588-5139



“We ensure the quality and efficiency of heat pumps with natural refrigerants by prototype development and testing.”

Hannes Seifarth,
technician, and
Philipp Bauer,
scientist.

More Information

Business Area

Publications

Projects

Hydrogen Technologies

Market Position

The global community intends to cease its emission of CO_2 by 2050 – this goal pushes hydrogen as a fuel into the limelight, as sustainably produced hydrogen and its derivates can replace fossil fuels. The enormous bandwidth of application possibilities for hydrogen as an energy carrier and storage medium, as well as a fundamental chemical, is now developing its huge potential.

Appreciable innovations are still necessary to achieve the required upscaling of the hydrogen economy, as the technological and commercial development of central elements of the value chain are currently in an early industrial phase. Thus, contributions from research and development – from fundamental materials questions up to innovative, scalable production processes – are needed to retain opportunities for German industry at all stages of the value chain.

With our expertise, we accompany industrial partners and clients in the development of efficient technology along the entire value chain. In addition, we carry out lifecycle and techno-economic analyses, in which we can develop and evaluate solutions for the production of hydrogen, its efficient storage and customized distribution.

Facts and Figures

Total staff	174
Journal articles and contributions to books	13
Lectures and conference papers	21
First patent applications	4

Leadership

Ulf Groos, Phone +49 761 4588-5202

Topics in this Business Area

Fuel Cell
Ulf Groos, Phone +49 761 4588-5202

Electrolysis and Hydrogen Infrastructure
Dr. Tom Smolinka, Phone +49 761 4588-5212

Sustainable Synthesis Products
Dr. Achim Schaadt, Phone +49 761 4588-5428

Our goal is large-scale production of PEM electrolysers. We are cooperating with national and international partners to reach this goal.”

Richard Lohmann, engineer in the HyFab project, and **Dr. Zohreh Kiaee,** project leader for fuel cell production.

More Information

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System Integration

Market Position

System integration plays a central role in the targeted transition of our energy supply to a net-zero energy system. Many components to provide emission-free energy are indeed competitive today – but their integration into a complete, trans-sectoral energy system is still a great challenge. The heat, electricity and mobility sectors will need to interact increasingly in future. This applies equally well to the energy supply of buildings and neighborhoods as to the establishment of interregional infrastructure to provide primary energy.

Intelligent systems integration takes the current situation into account: The large number of small PV systems places high demands on supply reliability; in addition, grid infrastructure should remain affordable. Here, flexibly controllable loads and the application of storage units, for instance in electric vehicles that can feed charge back into the grid, can interact in a digitalized operation management system. In the storage of renewably generated energy via intelligent control concepts, there is a high utilization potential for the coupling of the electricity and heat sectors. Further important concepts include the application of hydrogen by electrolysis for longer-term storage of energy and its reconversion into electricity. We research and develop corresponding solutions for the concrete energy transition in the local area and test them together with partners in living laboratories.

Facts and Figures

Total staff	83
Journal articles and contributions to books	15
Lectures and conference papers	53
First patent applications	1

Leadership

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

Topics in this Business Area

Energy System Analysis
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Integrated Energy Infrastructures: Electricity, District Heat, Gas
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Energy Data Analysis
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Flexibility Management of Energy Systems
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Climate-Neutral Industry
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Climate-Neutral Cities, Urban Districts and On-Site Systems
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Electric Mobility
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Living Labs
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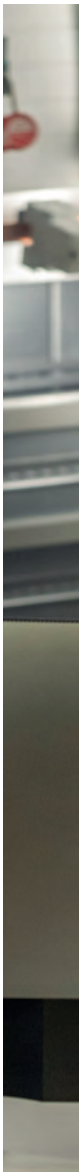


“We are conducting research on systems integration which brings all system components together in a digitalized grid infrastructure.”

Fabian Ernsting, B.Sc. candidate, and
Phillip Pütz, scientific student assistant.

More Information

Business Area

Publications

Projects

R&D Infrastructure

Fraunhofer ISE is equipped with excellent technical infrastructure. Laboratories with a floor area of 22,300 m² – including 900 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 access 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, the Institute 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) (see p. 48 ff.).

In our eight laboratory centers and four production-relevant technological evaluation centers, we develop new products, processes and services and optimize existing ones.

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 Organic and Perovskite Photovoltaics
- Center for Functional Surfaces
- Center for Outdoor Performance
- Center for Power Electronics and Sustainable Grids
- Center for Electrical Energy Storage
- Center for Heating and Cooling Technologies
- Center for Electrolysis, Fuel Cells and Synthetic Fuels

Quality control of a shingling process.

Accredited Laboratories

CalLab PV Cells

Calibration of Solar Cells

In CalLab PV Cells, we offer calibration services for a diverse range of PV cell technologies. The laboratory is accredited for solar cell calibration by the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body) and is 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.

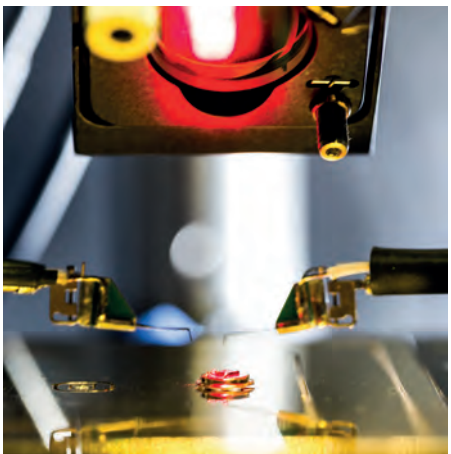
In recent years, we have further expanded our measurement facilities and can thus calibrate modern silicon solar cells up to an edge length of G12 very accurately. For several years, we have been working on measurement methods to determine realistic performance parameters for perovskite-based solar cells. We can thus carry out measurements for perovskite-Si tandem solar cells up to an edge length of M10. This is based on our many years of experience specifically in the area of III-V tandem solar cells. Primarily space, concentrator, and laser power conversion cells are at the focus of these measurements.

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.

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

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

cells@callab.de



Characterization of a laser power conversion cell.

CalLab
PV Modules

Calibration of PV Modules

CalLab PV Modules is the only accredited calibration laboratory for photovoltaic modules in Germany. Here, we calibrate PV modules for production lines accurately, quickly and reliably. In contrast to a classic measurement service, a calibration is distinguished by highest demands on measurement uncertainty and traceability. 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.

The expansion of our accreditation scope to include bifacial and large-format modules complements the previous product portfolio and provides an important pillar for quality assurance of future module technologies. 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. A central element in verifying and validating the measurement results is the stable calibration level over many years, which ensures reliability and certainty for our clients and project partners.

In addition, we are 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 under standard conditions using several outdoor test rigs equipped with trackers or in our laboratory with a solar simulator.

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Initial inspection of a PV module.

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, VDE, 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 yet 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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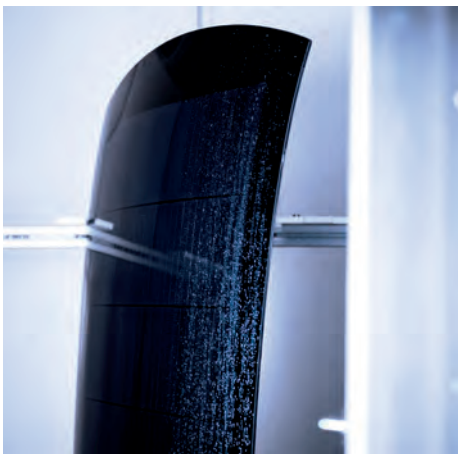

Testing a vehicle-integrated PV module.

TestLab Solar Façades

Optical and Thermal Characterization of Building Façades

In TestLab Solar Façades, we characterize transparent, translucent and opaque materials. We also test and evaluate the energy-relevant, thermal and optical properties of façade components and systems. The Lab encompasses both indoor laboratories with controlled boundary conditions, as well as an outdoor facility "CONTINENT" to test the thermal and daylighting performance of complete façade systems under real boundary conditions.

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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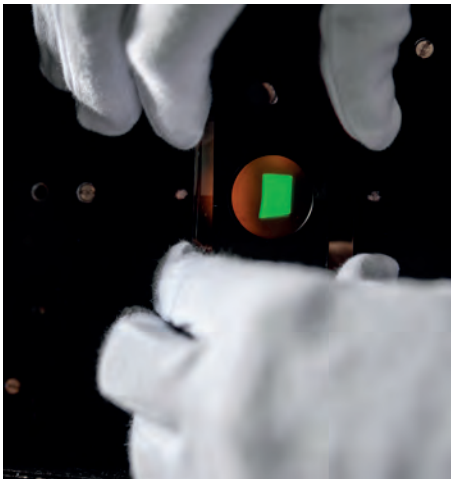

Illuminated sample at the aperture of an integrating sphere.

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 +60 °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 applying remote procedures, within the Solar Keymark certification programme.

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Solar collectors on the outdoor test stand.

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 m³/h to 5000 m³/h) can be conditioned in the temperature range from -15 °C to +50 °C and relative air humidity from 15 % to 95 %.

In our laboratory, which is accredited according to ISO/IEC 17025, we test systems according to all common standards and technical codes. Beyond standardized methods, we cooperate with our clients to develop individual, realistic measurement procedures.

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Measurement of a heat pump.

TestLab
Power Electronics

Characterization of Power Electronics Equipment

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

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

Furthermore, we offer our clients field measurements, for instance of large PV or wind power plants. For this purpose, we have six power 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 feed-in codes (e.g., for Germany, China or Great Britain) and determine the efficiency of power electronic equipment with high accuracy.

Steffen Eyhorn
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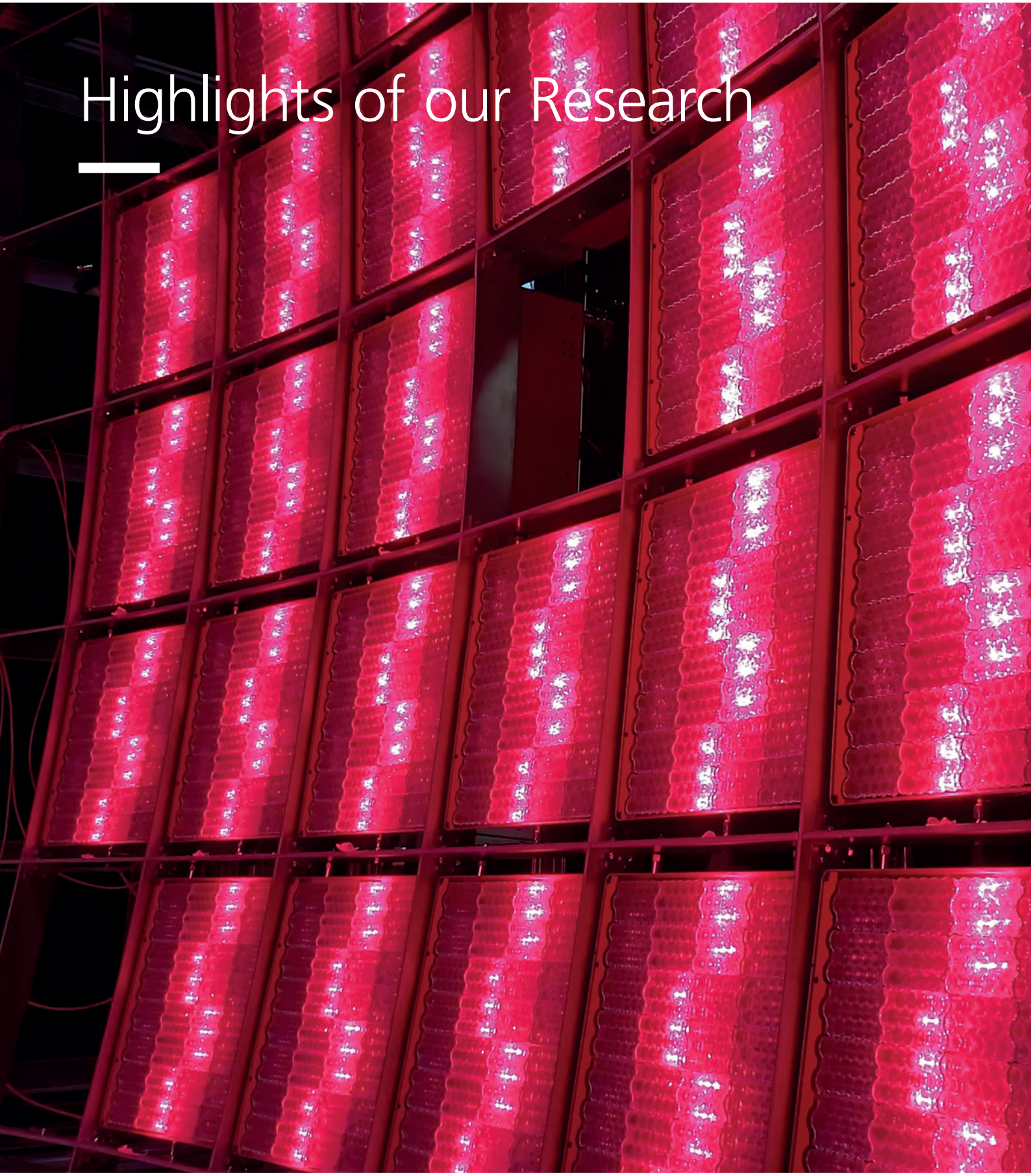
1 MW battery simulator in TestLab Power Electronics.

Highlights of our Research



“With our industrially relevant research and development, we aim to support rapid implementation of the energy transition.”

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

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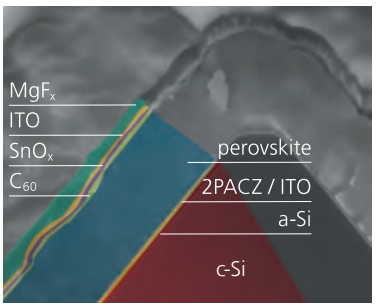
Highly Efficient and Scalable Perovskite-Silicon Tandem Solar Cells

Perovskite-silicon tandem solar cells have become promising technological successors to silicon solar cells. They extend the very mature silicon solar cell technology, as a perovskite with a large band gap is deposited on top of a silicon solar cell, so that better use can be made of the energy of the solar spectrum. On a laboratory scale, this type of perovskite-silicon solar cells has already achieved efficiencies exceeding 33 %. To produce such efficient solar cells, all of the cell layers must be finely tuned to match each other exactly and the interfaces must be optimized. We are tackling this task together with five other Fraunhofer Institutes in the Lighthouse Project, "MaNiTU".



Cross-section of a perovskite-silicon tandem solar cell under the electron microscope.

As not all of the previously applied laboratory production methods are suitable for industrial manufacturing, we are working intensively at Fraunhofer ISE on the development and evaluation of production methods that can be used for mass production. In the "PrEsto" project, the focus is on the so-called hybrid process, in which the perovskite absorbers are produced in a two-stage process. We have already achieved efficiencies of 30 % with this method. The advantages of this method are that the textured silicon solar cells that are usually used in the industry can be coated conformally and that scalable process technology is available. On this basis, we were able to produce a tandem solar cell in M2 format.

Based on this experience, we have now begun to establish an independent technological platform within the "Pero-Si-SCALE" and "LiverPool" projects, enabling the further development and analysis of cell and module designs as well as their production processes for perovskite-silicon tandem solar cells.

Due to the enormous variety within the perovskite group of materials and the associated opportunity to define the absorption properties over a wide spectral range, it is also possible to combine several different perovskite solar cells with a silicon solar cell and thus achieve still higher efficiencies than with only two materials. Triple-junction solar cells, which consist of one silicon sub-cell and two different perovskite sub-cells, are the subject of research in the EU-funded "Triumph" project and the "RIESEN" project. The high voltages and low currents of such solar cells reduce the power losses due to cell metallization and connection, and thus also reduce the material consumption of valuable silver or copper. At Fraunhofer ISE, we have now achieved an extremely high open-circuit voltage exceeding 2.8 V for this type of solar cell. This is an important step for the development of this new triple-junction solar cell.

The Pero-Si-SCALE, LiverPool and RIESEN projects are funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Perovskite-silicon tandem solar cell in M2 format.

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Progress in the Development of Organic Solar Cells with High Visible Transmittance

In the "See-Through-PV" project, we are developing organic solar cells with high visible transmittance, in cooperation with our partners from the industry and the University of Freiburg. In doing so, we use the unique optical properties of certain organic semiconductors which are transparent to light in the visible spectral range and simultaneously exhibit strong absorption in the near-infrared (NIR) range. This enables the production of semi-transparent solar cells which are homogeneous over their whole area. To increase their efficiency, the application of special electrode systems is needed.

Whereas the front electrode should be as transparent as possible over the entire solar spectral range, the back electrode should combine high visible transmittance with high NIR reflectance. To this purpose, we use an electrode system developed at Fraunhofer ISE, based on thin silver films, which possesses the desired optical properties and simultaneously features sufficiently high electrical conductivity. Concretely, we have used a layer stack of AZO/Ag/AZO/Ag/AZO, whereby AZO stands for Al-doped zinc oxide. The individual coatings are deposited by sputtering.

The photo-active organic material was applied from non-chlorinated solvents, as would be required in industrial production. A transparent, conductive polymer (PEDOT:PSS) is used as the upper electrode and is produced by our cooperation partner, Heraeus. By applying a new PEDOT:PSS formulation and adjusting the film thickness of the absorber, high visible transmittance was achieved. In addition, we succeeded in increasing the number of NIR photons that are reflected back into the active layer, by optimizing the back electrode. This increases the amount of current generated by the solar cell without decreasing transmission in the visible range.

As a result of these developments, we fabricated organic solar cells with an efficiency of 8.7 % and an average visible transmittance (AVT) of 46.3 %. The so-called light utilization efficiency (LUE) is often used to compare semi-transparent solar cells with different transmittance values with each other, quickly and simply. It is the product of the efficiency and the AVT. Our organic solar cells reach an LUE of 4.0 %. This is a very promising value, as the cells do not contain indium tin oxide and are processed using non-chlorinated solvents.

Due to the manifold possibilities of synthetic organic chemistry, it can be assumed that new, improved semiconductor materials will be found which enable further increases in efficiency. This opens up new application areas for organic photovoltaics, particularly in the fields of building-integrated photovoltaics and agri-photovoltaics. Thanks to their low weight, the ease of integration and their advantageous appearance, organic PV has the perspective of making a valuable contribution toward increasing public acceptance of integrated photovoltaics.

The See-Through-PV project is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Organic solar cell with high visible transmittance.

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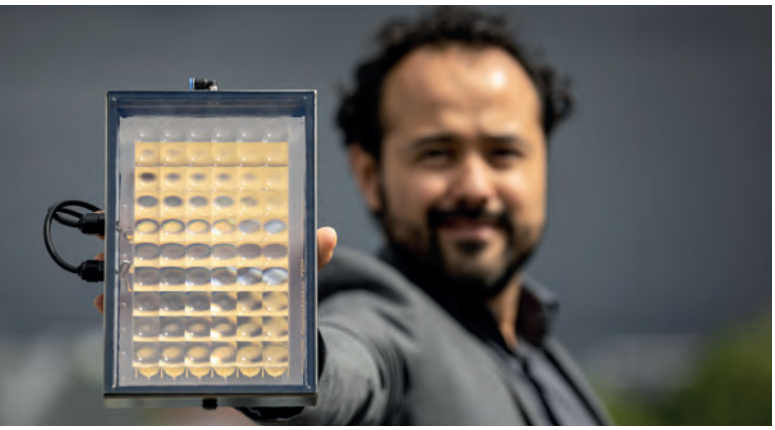
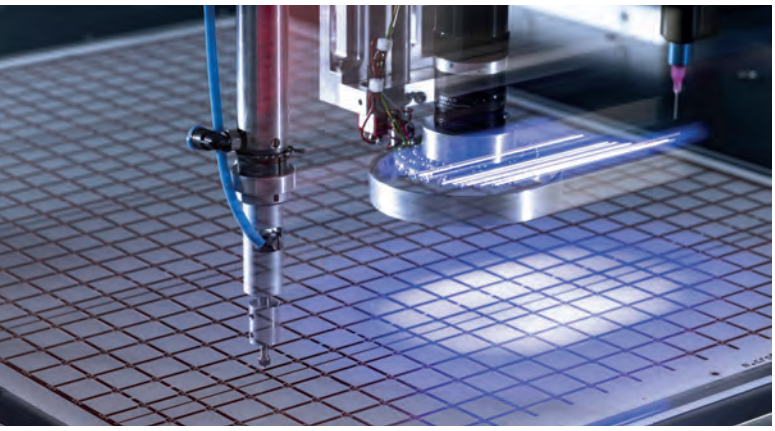
Development of Highest-Efficiency Micro-CPV Modules



Micro-CPV module developed at Fraunhofer ISE, with a module efficiency of 36.5 %, the highest efficiency for a module with industrial components from Europe.



Micro-CPV cells are positioned on the printed circuit board forming the module base. The solar cells can be accurately positioned due to self-alignment of the solar cell chips.

Concentrating photovoltaics uses lenses to concentrate direct solar radiation by factors of a hundred to a thousand and direct it onto extremely high-efficiency III-V multiple-junction solar cells. In our most recent module development at Fraunhofer ISE, which we call micro-CPV, we are using particularly small solar cells with an edge length of 0.585 mm. Although each cell generates only a small amount of power due to the small solar cell and lens areas, this feature means that we can use thin copper circuits to connect the solar cells electrically to each other and to remove heat. This saves material for additional cooling elements.

At Fraunhofer ISE we are developing the most modern, high-throughput processes for the construction and connection technology, which make it possible to position many components simultaneously and very rapidly on the base plates of the modules. At the same time, the tiny solar cells must be positioned exactly in the focus of the lenses. However, the surface tension of the molten solder under the solar cells helps us to align the components on the printed circuit. This phenomenon is called "self-alignment". This effect means that the required tolerances in the module can be met, even with a positioning accuracy of the solar cells in the range of 150 µm.

In 2022, we were able to measure the first modules of the new generation on our outdoor test stand within the "micro-CPV" project: Under concentrator standard test conditions (CSTC), we achieve an excellent efficiency here of up to 36.5 %. We used III-V solar cells, consisting of five sub-cells stacked on top of each other, from the AZUR Space company in Heilbronn. The III-V multi-junction solar cells were originally developed for satellites and then adapted to the conditions in concentrator modules.

The micro-CPV modules must track the sun very accurately, so they are particularly well suited for the solar belt of the earth. Here, we also foresee good synergy with the production of solar hydrogen. Furthermore, the high efficiencies and small solar cell areas of concentrating photovoltaics allow valuable resources and energy to be saved in their production. As the supply industry is located completely within Europe, concentrating photovoltaics guarantees a high degree of technological sovereignty and independence with regard to raw materials. Within the Fraunhofer Deeptech Accelerator AHEAD, we are currently evaluating the establishment of a new spin-off company for commercial further development of the technology.

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The micro-CPV project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

"III-V on PorGe": Inexpensive III-V Multi-Junction Solar Cells Based on Porosified Germanium

Compared to single-junction solar cells, III-V tandem solar cells feature higher efficiencies in converting sunlight to electricity. Their main components are different photo-active absorber layers. However, these are produced applying a relatively slow process, namely metal-organic vapor phase epitaxy (MOVPE), and expensive gallium arsenide (GaAs) or germanium substrates. In addition, the solar-cell processing is complex and has a low throughput. The substrate, epitaxial layer growth and processing each represent about a third of the total costs. Thus, each of these steps along the route to the final solar cell must become more cost-efficient. At Fraunhofer ISE, we have developed approaches which can lead to cost reductions.

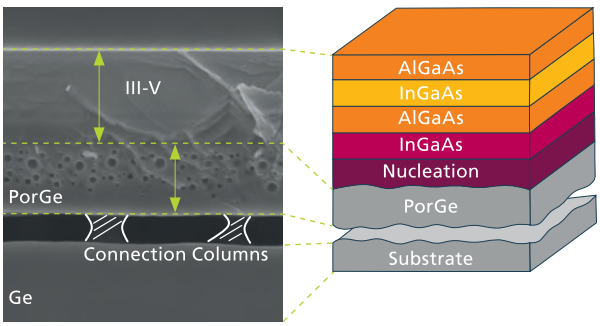
The germanium substrate is initially used in a thickness which is not needed for the final solar cell but is required to withstand the mechanical loads during processing. To significantly reduce the consumption of substrate material, we make use of electrochemical porosification followed by a high-temperature annealing process. During porosification, material is deliberately removed such that a porosity gradient is created. A controlled-fracture plane in the substrate is created by the annealing process. The final substrate thickness is reduced to app. 0.8–0.9 µm. The III-V cells are then grown on the modified substrate. After the solar-cell processing, the solar cell is separated along the controlled-fracture plane (see illustration). The initial substrate is then available to be re-used in the production cycle.

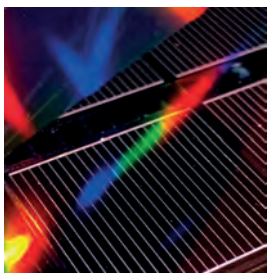
The relatively high costs of III-V epitaxy result primarily from the long processing times. Typical growth rates, e.g. for GaAs, are lower than 10 µm/h, for absorber thicknesses of up to 3 µm/h. We were able to demonstrate that growth rates exceeding 280 µm/h are possible with MOVPE after clever process optimization. In addition, it became evident that V:III ratios (ratio of group V precursors to group III) that are five times smaller are advantageous at growth rates > 100 µm/h and that the incorporation efficiency of the group III precursors can be increased by 60 %. For a growth rate of 100 µm/h, already an efficiency of 23.6 % has been demonstrated for the first single-junction GaAs solar cells. We are developing this approach further in the "H2DEMO" and "Vorfahrt" projects and transferring it to tandem cells.

Also, the costs for metallization (cell processing) can be clearly reduced by the mask-and-plate approach, as we were able to demonstrate in the "SALLI" project. Here, the mask is applied by material-saving inkjet printing and the metal is deposited by plating through narrow openings. Finger widths of only 10 µm have already been demonstrated with this approach. The first resulting triple-junction solar cells achieved efficiencies exceeding 30 %.

All of these developments that we have researched at Fraunhofer ISE, the re-use of the germanium substrates and the higher throughput rates for III-V film growth and solar cell metallization, lead to significant cost reductions for III-V tandem solar cells.

SEM image (left) of the schematic thin-film stack (center) after porosification, annealing and III-V epitaxy. Photo of a high-efficiency III-V / Si tandem solar cell with mask-and-plate front metallization (right).





The H2DEMO project was funded by the German Federal Ministry for Education and Research (BMBF). The SALLI project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

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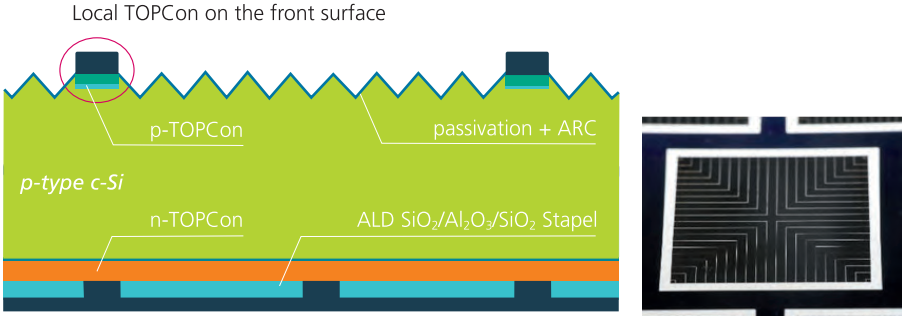
TOPCoRE Solar Cells on Gallium-Doped Cz-Si Wafers (p-type)

In industrial solar cell production, a clear trend away from PERC solar cells on p-type wafers toward solar cells based on n-type wafers with charge-carrier-selective contacts can currently be identified. At present, TOPCon solar cells represent the largest share – technology, which was developed at Fraunhofer ISE. The industry's current choice of n-type Cz-Si is influenced by the higher wafer costs compared to p-type Cz-Si wafers.

At Fraunhofer ISE, our record efficiencies for laboratory TOPCoRE solar cells on p-type FZ-Si wafers and simulations were early demonstrations that these have a higher efficiency potential than TOPCon solar cells of n-type silicon. During solar cell production on p-type wafers, a phenomenon occurred which we called light-induced improvement (LII) and have investigated in greater detail. In LII, solar cell parameters improve under illumination within seconds, which presents challenges to the classification of solar cells for module construction. To facilitate a possible technological transfer to industry, our goal was to identify the cause of the rapid improvement. To this purpose, we prepared test structures which represent the different regions of a TOPCoRE solar cell: A) back surface (tunnel oxide + poly-Si(n^{++}) + SiNx:H), B) front surface of the TOPCoRE solar cell, C) TOPCoRE solar cells, D) I-V_{oc} test architectures. The test architecture which represents the back surface (A), did not show any rapid improvement under illumination, although extraordinarily long charge-carrier lifetimes and implicitly high open-circuit voltages were measured. This implies that neither the back-surface passivation nor the gallium-doped p-type wafers were the cause for the rapid light-induced improvement. However, all other architectures (B, C and D) displayed LII.

LII can already be observed before metallization or the firing process for metal contacts. In addition, we demonstrated on the symmetric test architectures which represented the TOPCoRe front surface that LII occurs, regardless of whether high-temperature processes like boron diffusion and poly-Si annealing are applied or not. It is known from literature that AlO_x, which is used to passivate the front surface, can lead to LII – but the reported periods of time were many times longer. It is also known that e.g. the bonds between the atoms of Fe-Ga or Fe-B pairs break under illumination, resulting in the formation of interstitial Fe_i.

As TOPCoRE solar cells on p-type silicon can contribute to reduced production costs for solar energy, we will continue to conduct further research at Fraunhofer ISE to identify the cause for LII. In doing so, we aim to pave the way for the PV industry to adopt this solar cell structure.



Structure and initial cell results for TOPCoRE laboratory prototype solar cells with local p-TOPCon front contact passivation.

front contact passivation	J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	η [%]
local TOPCon	41.7	728	81.1	24.6

Internal measurement, 4 cm² designated area, without a double-layer MgF_2 anti-reflective coating (ARC).

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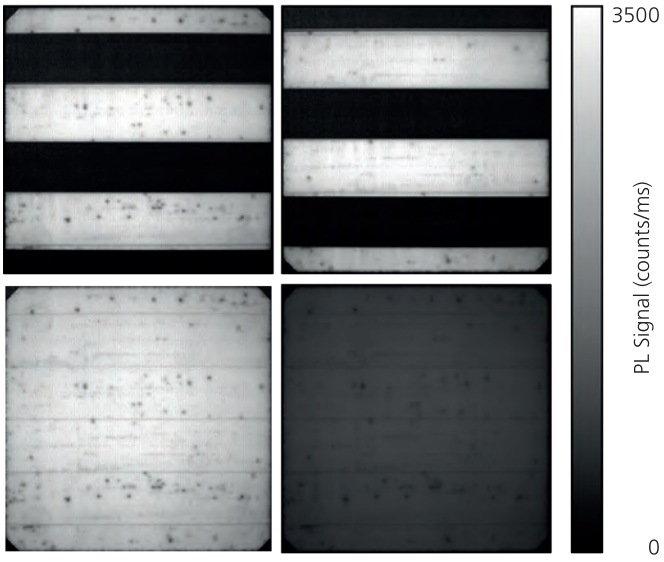
Contact-Free Inline Measurement of Solar Cell IV Characteristics Assisted by Artificial Intelligence

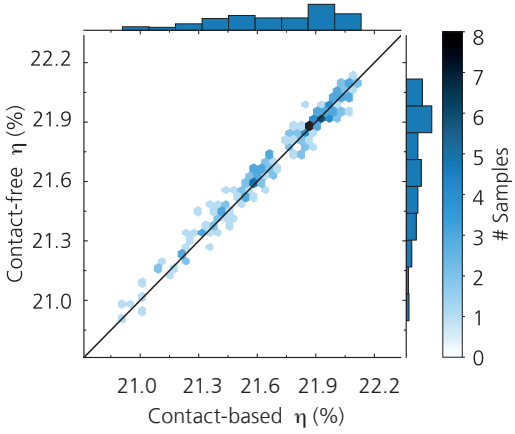
One option to reduce the production costs of solar cells is to increase the throughput of all production facilities. In the "NextTec" project, we have thus investigated the potential to accelerate the production process. Measurement of the current-voltage (IV) characteristic at the end of the production line is mandatory but reduces the throughput considerably, as the cells must be contacted for the measurement, which takes more time than the measurement itself. In the previous Annual Report of Fraunhofer ISE for 2022/23, we already presented a physical model for contact-free IV measurement of solar cells.

An alternative contact-free approach, which is based on artificial intelligence and extends image analysis, requires less and, above all, only rapid inline-compatible measurement technology, such that a throughput of up to 20,000 cells/hour is possible – and thus an increase in throughput by about a factor of four. Our process is based on a series of photoluminescence measurements under varying illumination intensity and shading (see illustration) and a spectral reflectance measurement. Each measurements provides information on different quality properties of the cell, although relevant characteristic data cannot be derived simply from individual measurements. A convolutional neural network was thus developed to combine all of the spatially and spectrally resolved data from the contact-free measurements and determine the relevant quality characteristics of the solar cell, such as efficiency, open-circuit voltage or also the complete IV characteristic of the cell, from the patterns found in the multi-dimensional data. In an extensive study, a data set was created with 4500 samples to train and evaluate the models. Analysis of the models demonstrated that very good agreement exists between the contact-free, AI-based predictions and the results from measurement instruments on contacted cells (see graph). Furthermore, we showed that cell sorting based on contact-free measurements resulted in the same module quality as with contact-based measurements.

Compared to contact-based measurements, the contact-free IV measurement has numerous advantages with respect to throughput, maintenance costs and down times. Elimination of the contacting step means that the measurement time can be reduced. In addition, the mechanical pressure exerted by the contact bars on the cell is avoided, reducing the breakage rate and thus the down time of the production line. In addition, costs due to wear and maintenance are avoided by dispensing with contact bars.



Partly shaded (upper row) and homogeneously illuminated (lower row) photoluminescence measurements of an example cell.



Comparison of efficiency μ as determined by contact-based and contact-free measurements.

The NextTec project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

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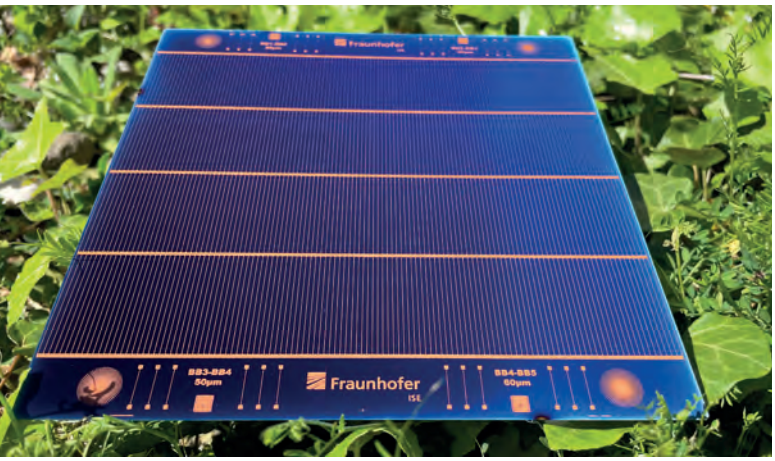
Saving Silver – a Scarce Raw Material: Copper Electrodes for Sustainable TOPCon Solar Cells



TOPCon solar cell metallized with purely copper-based paste (test layout).

The increasing share of photovoltaics in the global energy mix demands higher efficiencies and sustainable production processes. To conserve valuable resources, we at Fraunhofer ISE have investigated path-breaking approaches for more sustainable metallization processes for solar cells. High-efficiency solar cell concepts, such as the TOPCon technology developed at Fraunhofer ISE, are currently increasing their market share. However, they still have the disadvantage that they need significantly more silver than previous concepts. As a consequence, a scarcity of silver could lead in future to clear price increases and even jeopardize the total global production volumes.

Up to now, work has concentrated primarily on producing increasingly fine "fingers" with the established screen-printing processes, so that the amount of silver used could be reduced (fine-line screen printing). In this R&D area, have repeatedly achieved new record values, which were subsequently reflected in industrial production. An alternative to silver is copper – it is appreciably less expensive and has a comparable conductivity. If some of the silver in the printing pastes is replaced by copper, much of the previous production technology can remain unchanged. Because copper oxidizes very quickly and is thus more difficult to handle, we initially concentrated on silver-coated copper particles. In the meantime, good results can also be achieved with silver/copper blends or purely copper-based pastes. In the first experiments, we initially tested a printed copper metallization for the back of TOPCon solar cells. These tests proved that the same performance could be achieved as long as an extemely small amount of screen-printed silver was used for the contact layer. This approach saves up to 45 % silver per cell and can be adopted in industrial production in the near future.

Electro-plating with metals is an alternative approach from which silver can be almost completely eliminated. A metal contact is created by laser ablation and electro-plating of nickel, copper and silver. We have tested electro-plated nickel-copper-silver contacts on industrial TOPCon solar cells, thereby demonstrating a 90 % reduction in silver consumption and efficiencies exceeding 24 %. The cells have already been further processed with soldered contacts to form 60-cell modules. Based on these successes, we commissioned high-throughput pilot electro-plating equipment at Fraunhofer ISE within the "Indianapolis" project. The goal now is to develop these results further in close cooperation with industrial partners so that the sustainable TOPCon metallization with copper electrodes can become established.

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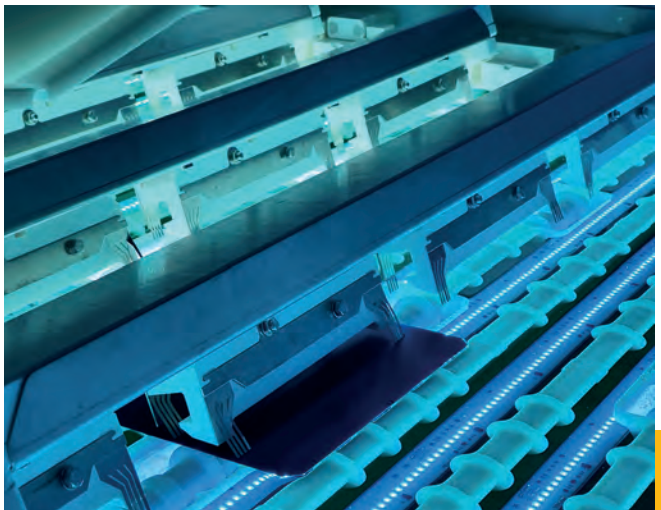
In 2023, a new prototype facility for research on cell metallization by nickel-copper-silver electro-plating was commissioned at Fraunhofer ISE.



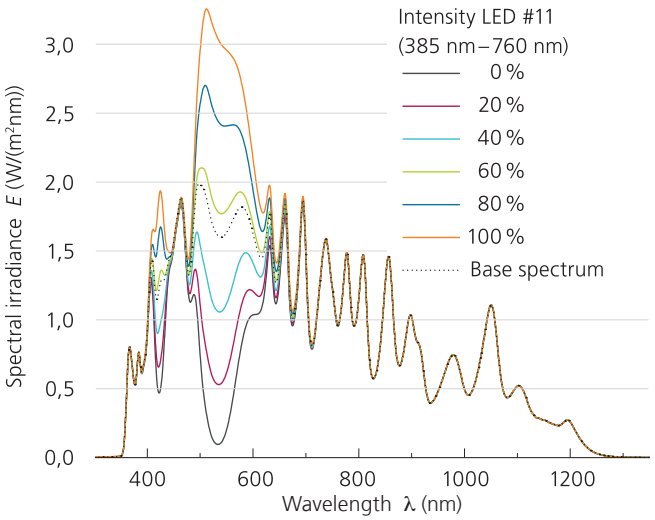
Calibration and Electrical Characterization of Perovskite-Silicon Tandem Solar Cells and Modules

To pave the way to industrial production of highly efficient perovskite-silicon PV modules, the tandem solar cells and modules must be measured reliably. This is the pre-requisite both for objective comparisons between different cells and modules and also good physical understanding of technological improvements. However, calibration here is more difficult than for conventional silicon PV modules.

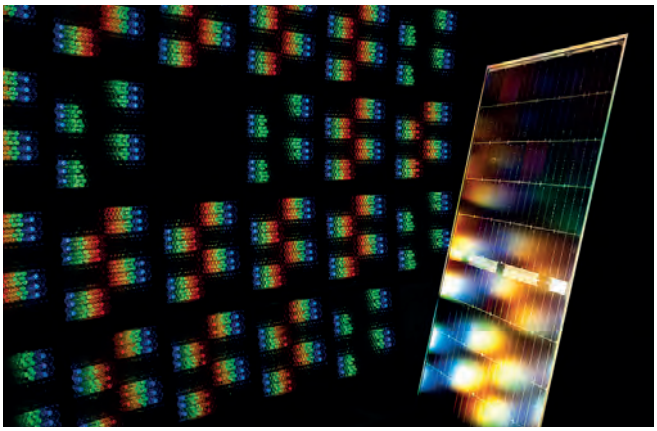
At Fraunhofer ISE, we are meeting this challenge in CalLab PV Modules with a globally unique, LED-based solar simulator, which we took into operation in 2023. In contrast to conventional solar simulators based on xenon lamps, the spectral properties of the light source can be set accurately within the range from 340 nm to 1650 nm by individually controlling 26 separate color channels. Modules with an area of up to 250 cm x 130 cm can be tested. The new challenge is now to qualify this solar simulator for the accurate measurement of modules based on different tandem cells and to develop appropriate testing routines.

In multi-junction solar cells, in which cells with different spectral properties are stacked on top of each other, the measurement spectrum must be adjusted such that each sub-cell generates exactly that current which it would supply under the standardized AM 1.5 solar spectrum. The control and implementation are not trivial, as the color channels mutually influence each other strongly due to thermal interactions, and various non-linearities and temporal deviations occur during the measurement.

At Fraunhofer ISE, we have comprehensively investigated and described these interactions. This created the basis to define control profiles for the LED array that are individually adapted to the test object being measured. We verified the procedure for spectral adaptation of LED-based solar simulators by a measurement comparison with an established three-source solar simulator for cell calibration. Furthermore, very good agreement was achieved between theoretically calculated and actually measured simulator spectra, resulting in reduced measurement uncertainties for tandem calibration. This is an important milestone toward the establishment of accurate and traceable performance measurements for perovskite-silicon tandem modules.



Measurement of the spectral irradiance of color channel #11 (385–760 nm) for different intensities. To characterize the spectral properties of different LEDs under real operating conditions, these are not characterized separately, as is the usual approach, but within a composite base spectrum with contributions from all LEDs.



The new solar simulator marks a milestone toward establishment of a standardized procedure for calibrating perovskite-silicon tandem modules.

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PV Canopies for Roads – an Important Building Block for the Energy Transition

Demonstration of a PV canopy for roads at the Hegau-Ost rest area, Baden-Württemberg, Germany.

Photovoltaic installations over motorways can make a significant contribution toward climate neutrality with their solar-generated electricity. Within the "PV-Süd" project, we at Fraunhofer ISE have cooperated with the Austrian Institute of Technology AIT and the company, Forster Industrietechnik GmbH, to develop, plan and implement a demonstration PV canopy for roads.

The pilot installation is located over the transit lane of the Hegau-Ost rest area on the German A81 motorway. In preparation, the project consortium had developed and tested the suitability of and the requirements on the PV modules and the sub-structure for the road canopy in laboratory experiments and by simulation. In doing so, the high demands of the transport sector were taken into account, e.g. protection against impact and fire. The 12 m x 14 m area of the PV module canopy, which is located about 5.5 m above the road level, is mounted on a steel structure. The PV modules are configured to form a shed roof to guarantee a high electricity yield as well as ensuring water run-off. As the glass-glass PV modules are authorized for overhead glazing, it was possible to integrate these into the construction without additional safety measures. The transparent gaps between the solar cells transmit light onto the road surface. Altogether 96 PV modules with a total power of 30 kWp have been installed.

Within the PV-Süd project, we will investigate the yields, the economic viability and the potential advantages of road canopies. Applying the assumed costs and scaling effects for the PV generator, specific system costs of less than 5000 €/kWp are possible. The sub-structure plays a decisive role, as this has less potential for the scaling effects of industrial production. On the basis of the potential power of 30,000 kWh/year fed into the grid by the demonstration canopy, which was calculated during the concept phase, the economic viability can be determined as a function of the feed-in tariff. Due to the high costs of the sub-structure, PV road canopies cannot compete economically with conventional ground-mounted installations. Nevertheless, they make use of already sealed areas of transport infrastructure and could amortize themselves over the lifetime of the sub-structure by "re-powering" with several generations of PV modules, which has a positive effect on their ecological footprint. This is particularly relevant for lower-priority road traffic, e.g., within built-up areas or over cycleways, as there the sub-structure can be reduced in comparison to locations near motorways.

PV road canopies for high-priority roads (particularly motorways) are an option that is fundamentally interesting where the electricity can be used directly, e.g. near tunnels or rest areas, as the load profile for a tunnel matches the generation profile of PV modules well. The partial transparency of the canopies also helps with visual adaptation by vehicle drivers to the darkness in the tunnel.

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Detail of the translucent modules of the demonstration PV canopy at the Hegau-Ost rest area, Baden-Württemberg, Germany.

Climate-Resilient Floating Power Plants

Floating PV (FPV) is a relatively new technology in Europe – with appreciable potential at a global level. Floating PV power plants consist of PV modules which are located on floating sub-structures on water. It must be assumed that FPV systems affect the hydrology and the ecosystem of the water bodies but the concrete effects of floating PV have not yet been adequately researched. In particular, the influence of FPV on the climatic resilience of the water body is still unclear. This resilience is endangered as a result of climatic change: The thermal properties of lakes will change in the foreseeable future, which can negatively affect the mixing of different water layers and their ecological quality. It is also to be expected that the climatic changes will compromise the function of lakes as sinks for carbon. Thus, we at Fraunhofer ISE have investigated the effects of FPV on thermal behavior, water quality and evaporation in various studies.

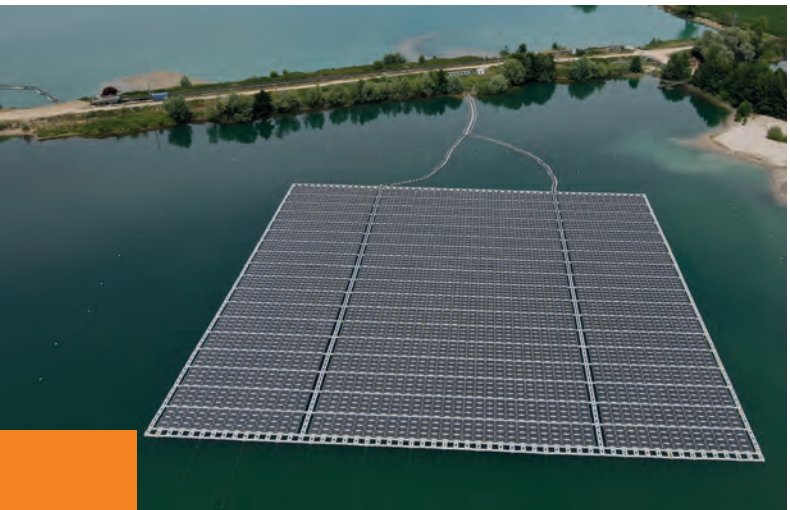
The Maiwald Lake is one of numerous former gravel pits in the Upper Rhine Valley. In a field study, the local FPV system and its surroundings were monitored to document changes in the thermal properties of the lake. Effects were observed particularly in the upper water layers – down to a layer thickness of five meters. Thus, the water underneath the system was up to 2.8 K cooler during the day of hot periods, whereas it was up to 1.4 K warmer during the night due to reduced thermal emission. When systems covering different proportions of the water area were modeled, it became evident that larger systems would result in less stable thermal stratification and shorter stratification duration in the lake. Thus, these systems would act to mitigate the anticipated effects of climatic change.

The "FPV4Resilience" project investigates the extent to which FPV can increase the climatic resilience of lakes. An extensive monitoring scheme was established at the locations of various European FPV power plants, which differ with respect to the FPV system design and the type of lake. Only preferred locations for the installation of floating PV, such as gravel pits, sand pits or dams, were taken into account. The project goal is to derive a definition of the climatic resilience of lakes from the interaction of floating PV with the lake and hydrological and meteorological characteristics. Finally, simulation will be applied to determine the Pareto optima of electricity yield and climatic resilience, and compared to the available measurement data.

Lake Nasser is one of the largest artificial lakes in the world and is traversed by the border between Egypt and Sudan. It is to be assumed that floating PV offers great potential to reduce evaporation in arid regions with large water reservoirs. Thus, we carried out a modeling experiment in which different areas of FPV systems on the reservoir were simulated and the associated water savings were calculated.

Depending on the system size, these water savings amounted to 600–5900 million m³/a (7.67 m³/(a * kWp) on average). In addition, an optimized water management program for agricultural irrigation was derived from the simulation of different scenarios. Electricity yield simulations revealed that covering 45 % of the lake with floating PV would – on average – meet the current electricity demand of Africa.

The FPV4Resilience project was funded by the Sustainability Center Freiburg.



Floating PV system on a former gravel pit near Leimersheim, Rheinland-Pfalz, Germany.

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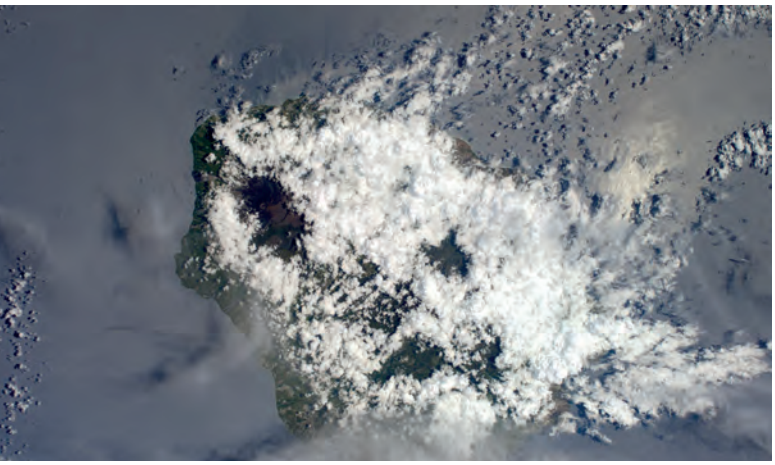
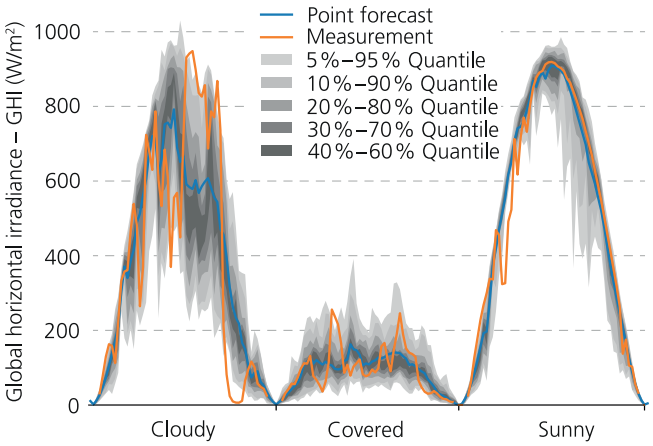
Probabilistic Forecast of Solar Irradiance Based on Satellite Data



Clouds over the French island of La Réunion, located in the Indian Ocean; photographed from the ISS space station.



Probabilistic forecasts (gray regions) of the global horizontal irradiance (GHI) from 9th to 11th May, 2018 in Payerne, Switzerland.

Electricity generation from the sun and the wind depends on the weather – this influences the electricity supply and its distribution. Meteorological forecasts are helpful in improving the integration of electricity from renewable sources into electricity grids. However, the forecasts are always subject to some uncertainty. Probabilistic forecasts provide probability distributions instead of a single predicted value (point forecast). Using these distributions, uncertainties can be predicted, minimizing risks and costs.

In the "SOLREV" project, we are developing probabilistic forecasts of solar irradiance on the basis of established point forecast procedures. As part of the project, we are participating as the German partner in PVPS Task 16, "Solar Resource for High Penetration and Large Scale Applications" of the International Energy Agency (IEA), contributing to the topic of solar energy meteorology. Within the Task, we participated in an international benchmarking exercise on probabilistic forecasts, which was conducted in 2022 under the direction of the Université de La Réunion.

The uncertainty of solar irradiance forecasts depends on the weather conditions, particularly the variability of the cloud cover. Situations with a clear sky or a completely overcast sky lead to low uncertainty, whereas intermittent cloud cover results in large uncertainties (see graph). To reflect these different uncertainties, we search for similar situations in the past on the basis of historical point forecasts and derive the sought probability distributions from the corresponding measured values.

We calculate our point forecasts from three data sources by combining current measured values, satellite-based forecasts and numerical weather predictions (NWP) with machine-based learning methods. The satellite-based predictions are better than those based on measured values after about 30 minutes and are better than NWP-based procedures up to about two hours. In this way, the forecast horizon from 15 minutes to six hours is optimally covered. Whereas measured values and NWP are already established as bases for probabilistic prediction, the use of satellite-based forecasts is new in this context and led in the benchmarking exercise to a significant improvement in the probabilistic forecast quality.

The SOLREV project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

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Digitalization of Research Data Illustrated by Innovative Battery Technologies as an Example

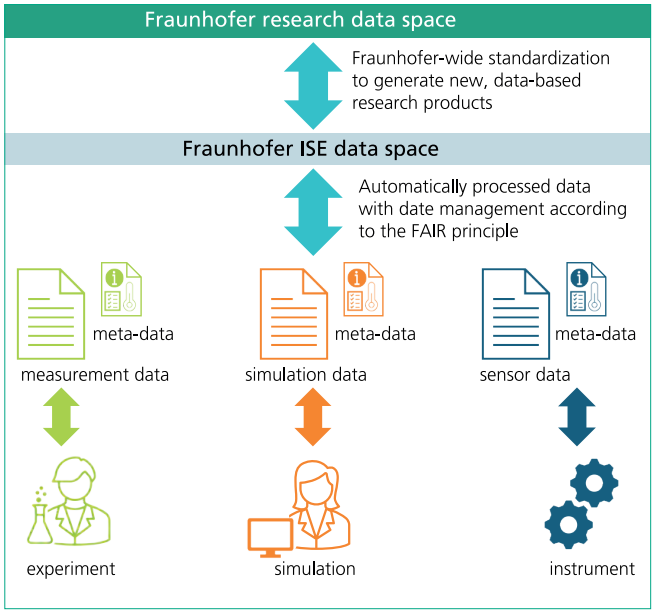
The digital transformation in research opens up numerous possibilities to develop innovative, data-based services and new, digital business models. For the Fraunhofer-Gesellschaft, this change presents a challenge and an opportunity at the same time, as digitalization requires not only the establishment of suitable infrastructure but also a working-culture transformation to standardized data management. Consistent and logical digitalization of research and development activities will be inevitable in future: on the one hand, to meet requirements of national and international funding agencies on data handling and on the other, to survive in international competition. At Fraunhofer ISE, we are working toward this goal within various projects on battery research, including the "Samba" and "Quaze" projects.

Different types of research and development data are generated in the projects. These are gathered, e.g., during the end-of-line quality control of battery cell production or in the battery test laboratory, where we generate extensive time series in long-term investigations of battery cells and modules. In addition, we carry out short-term measurements with complex test facilities. At present, the resulting research data are usually acquired, analyzed and saved according to individual procedures.

The researchers decide where and in which format the data will be stored and analyzed. In practice, this means that raw data are saved without the meta-data which document the exact experimental procedure, ambient conditions or the experimental set-up. At a later time, these data cannot be found by other researchers at all, or only after considerable time and effort, and can only be inadequately interpreted. Often, this excludes re-use of the data. At the same time, it is often complicated to record meta-data, as they are generally not acquired automatically. In addition, at the time of the measurement, it is often not foreseeable which data will be relevant for a second evaluation. Nevertheless, good scientific practice requires accurate documentation and traceability to allow experiments to be reproduced and understood.

Different Institutes of the Fraunhofer-Gesellschaft are thus working on concepts for standardized and automated data storage. As an example, Fraunhofer ISE is involved in initial joint conceptualization within battery research. The goal is to develop a data space that is accessible from different Institutes and allows standardized storage and linkage of data according to the FAIR principle, meaning findable, accessible, interoperable and reusable. Establishment of a digital research data infrastructure not only advances the strategic development of digital competence and improves the quality of current service offers. It also provides the opportunity to develop completely new, digital business models that transcend the boundaries of individual Institutes.

Good data management facilitates data analysis and allows large amounts of data to be evaluated by applying artificial intelligence, approaches which we are following together with industrial partners in the "Samba" and "Quaze" joint research projects.



Schematic diagram of the data space, which automatically records data together with meta-data, processes them and organizes them according to the FAIR principle.

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First Medium-Voltage String Inverter in the World for Future Large-Scale PV Power Plants

The planned expansion of photovoltaics will demand large quantities of raw materials, including copper and aluminum for cables and transformers. Within the "MS-LeiKra" project, we at Fraunhofer ISE have developed a string inverter which features a significantly higher output voltage. This can lead to major savings in consumed resources, as the higher voltage results in a lower current and thus smaller cable cross-sections.

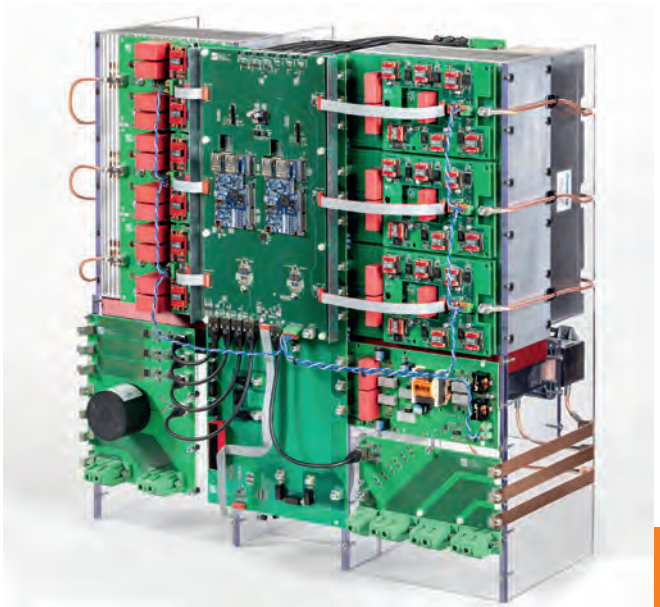
String inverters today use output voltages (line to line) between 400 V_{AC} and 800 V_{AC}. In the past, the voltage of the string inverters was repeatedly increased together with their increased power rating. For a given power value, a higher voltage results in a lower current and thus smaller current-dependent losses. Recently, however, there have not been any further increases in the voltage despite continued increases in power. This has two reasons: firstly, the challenge of constructing a highly efficient and compact inverter for higher voltages on the basis of silicon semiconductors; secondly, the currently existing PV-specific standards apply only for the low-voltage range. This ends at 1500 V_{DC} or 1000 V_{AC}.

The potential savings which could be achieved by raising the voltage higher are illustrated by the photo below (left). This is based on the assumption of a string inverter with a power rating of 250 kVA. For the output power of 800 V_{AC}, which is possible today, DIN VDE 0298-4, Table 9.2 demands a minimum cable cross-section of 120 mm². If the voltage is increased to 1500 V_{AC}, the cable cross-section decreases to 35 mm². For an increase to 5000 V_{AC}, only a copper cable cross-sectionof 4 mm² remains as a requirement. As cable lengths of double-digit kilometers are installed in a large PV power plant, enormous amounts of material can be saved by applying this measure.

In order to overcome the identified hurdles, we have developed the first medium-voltage string inverter in the world and successfully taken it into grid-connected operation (see photo below, right). The inverter has an output voltage of 1500 V_{AC} for a rated power of 250 kVA. It implements a two-stage design. The step-up converter for a PV input voltage of 1.7 kV to 2.4 kV is based on 3.3 kV silicon carbide (SiC) semiconductors. The inverter stage was constructed with hybrid ANPC modules (Active Neutral Point Clamped). Four silicon and two SiC semiconductors are applied here. This topology allows the great advantages of SiC to be used for only minimally higher costs. Using the demonstrator, it was shown that higher voltages can be handled technologically and that work is now needed to adapt the standards accordingly.

Comparison of minimum cable cross-sections for 250 kVA for different voltages.

The MS-LeiKra project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).



Medium-voltage string inverter for future large PV power plants. Power: 250 kVA, output voltage: 1500 V_{AC}, PV voltage: 1.7 kV_{DC} – 2.4 kV_{DC}.

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Electromagnetic Transient Modelling (EMT) of Inverters Applying Standardized Interfaces

The rapid expansion of photovoltaic and wind power plants as well as battery storage units and electrolysers presents a challenge to stable operation of our power supply grid. In contrast to conventional power plants, such as those based on synchronous generators, these inverter-based systems behave dynamically – their behavior is mainly defined by software-based control algorithms. In general, this situation is advantageous, but it requires a harmonized set of regulations to ensure interoperability. In this context, test and validation methods are essential to allow the compliance of system behavior to be checked.

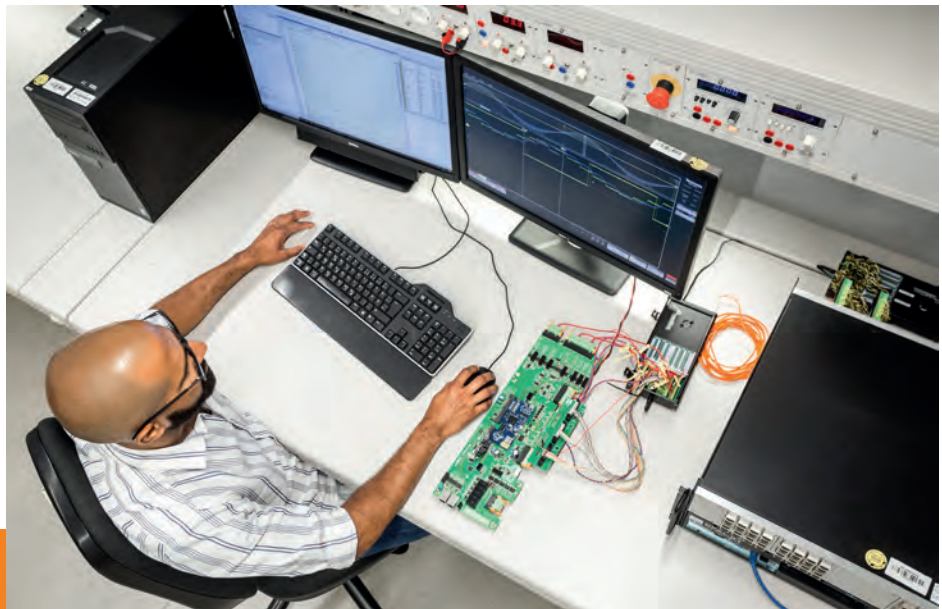
Different approaches to validate the system behavior are available. A trivial procedure is to measure the system in a testing laboratory under different operating conditions. However, complete characterization can only be achieved to a limited extent, for example, because the conditions at the system grid connection point depend on many factors. For large power systems, the first challenge is to find a testing laboratory with a sufficiently large capacity. Simulation-based analysis presents an alternative. Electricity grids can be modeled holistically by using suitable simulation environments. This is often done by applying highly dynamic electromagnetic transient simulation (EMT), particularly in the sector of power transmission and distribution operation.

When system models are exchanged, e.g. between grid operators and system manufacturers, two essential challenges are encountered: firstly, the control algorithms, which define the system behavior, belong to the proprietary intellectual property of the given manufacturer; secondly, a form of compatibility is favored which is independent of the simulation environment.

To overcome these challenges, Fraunhofer ISE has cooperated with TransnetBW GmbH to develop procedures to encapsulate the control algorithms by compilation into dynamic link libraries, so-called DLLs. The advantage of this procedure is that the control algorithm is no longer in a form which can be read or understood, such that the intellectual property of the manufacturer is protected. A further central aspect in the development of system models is the incorporation into any arbitrary simulation environment. To this purpose, the suitability of the proposed interface specification, ENTSO-E Standardized control interface for HVDC SIL/HIL conformity tests, was analyzed for general inverter-based systems.

For the example of a three-phase 500 kVA inverter, we have demonstrated how encapsulated DLL models can be created and standard interfaces for highly dynamic EMT simulations can be implemented. Investigations were conducted both of purely offline simulations (software in the loop; SIL), using the PSCAD simulation environment as an example, and also of the suitability of standard interfaces for hardware-in-the-loop (HIL) applications. We validated the generated models and simulations on the basis of high-resolution laboratory measurements of the real system.

Control hardware validation using hardware-in-the-loop (HIL) applications and a standardized interface.



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Effects of Distributed Electricity Storage Systems on the Low-Voltage Grid

So-called prosumers not only consume electricity but also produce it and participate increasingly actively in the energy market. An example for prosumers is given by the operators of "balcony power plants" on building façades and roof-mounted PV systems, which have recently become much more numerous. Particularly in new building zones, heat pumps for space heating have recently been added to the electricity consumption side; the number of electric vehicles is also increasing rapidly. These new electric components are increasingly being actively controlled by energy management systems to minimize the costs for electricity.

In an energy system that is based more and more on renewable energy sources, flexibility on the demand side and thus the behavior of prosumers is becoming increasingly important. In general, energy management systems control consumption such that as much electricity as possible is drawn from the prosumer's own photovoltaic system. Another option is to optimize the use of electricity for the electric vehicle, the storage battery and the heat pump according to the fluctuating prices of dynamic tariffs. Increasingly, commercial enterprises are also evolving into prosumers by orienting their consumption toward their own photovoltaic electricity generation, to become less dependent on the electricity market.

In the "MAPSEN" project, we at Fraunhofer ISE are applying models to investigate how the increasing number of prosumers affects the electricity markets and grids. The German electricity grid is not designed such that a large number of prosumer systems like photovoltaic systems and electric vehicles can be operated uncontrolledly. This would only be possible if the electricity grid were greatly extended and can be illustrated by an example: The changes in the electricity system would mean that 767 m of cables would have to be installed in an example rural area with 1057 customer, corresponding to 2.5 % of the entire length of installed cables in the area. In addition, three of the total of 16 transformers (19 %) would need to be replaced. These expansion requirements illustrate the enormous challenges which will confront the distribution grid operators in coming years.

To aid grid integration, we propose grid-supportive behavior of prosumers as a solution. This means, for example, that prosumers charge their storage batteries when the sun is shining strongly. Or they permit the grid operator to delay the charging of electric vehicles until the night, rather than during the evening, immediately after many car drivers have arrived at home. According to our calculations, these measures or behavior changes can reduce the peak loads on the grid and grid expansion costs would decrease by more than 30 %. In the "MAPSEN" project, we are developing tools which will help grid operators to quantify the behavior of prosumers and the effects of grid-supportive incentives.

The MAPSEN project is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Solar modules on balconies are becoming increasingly popular. At Fraunhofer ISE, we are investigating how grid-supportive integration of this type of prosumer systems can be designed.

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New Processes to Extract Raw Materials from Geothermal Brines

Lithium is a raw material which is essential for the energy transition and thus of great strategic economic importance. As the global lithium demand will increase drastically by 2030, new processes are needed to obtain it – particularly as Germany is currently solely an importer and thus dependent on international delivery chains.

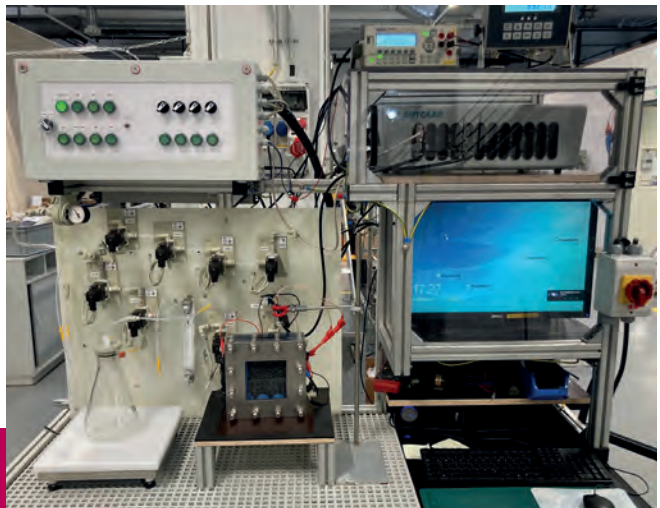
German geothermal springs can be a source, not only of heat, but also of raw materials like lithium, which could contribute to strategic security of raw material resources in future. At Fraunhofer ISE, we are thus developing process technology to extract valuable materials from geothermal brines. One possibility is to concentrate the raw materials, which are usually present in very low concentrations (the lithium content in the Upper Rhine Valley is about 160 mg/l), to values where precipitation is possible. The challenge thereby is to control the crystallization of other materials like silicates so that the systems do not become blocked.

In the German-Chilean "BrineMine" project, we have developed a process technology chain in which the silicate phases are initially chemically stabilized, before the first concentration process (by a factor of 8) occurs by reverse osmosis. Whereas the permeate is available as fresh water, the silicate in the concentrate is precipitated out by the addition of calcium and the precipitates are separated off via a rotary vacuum filter. Further processing and valorization of the silicate is conceivable. The concentrate from the reverse osmosis is then further concentrated by membrane distillation by a factor of up to 16. The heat needed to drive the distillation is obtained directly from the geothermal brines. In 2021, we successfully commissioned a demonstration system in a geothermal power station in Insheim in Rheinland-Pfalz, Germany – and another one in thermal springs in Puyehue, Chile.

In the demonstration system in the geothermal power station in Insheim, precipitates are separated by a rotary filter and transported out.

Furthermore, we are working on the development of highly selective separation processes which can also run under high temperature and pressure conditions, so that we can specifically extract individual elements directly from the brine. To this purpose, we are cooperating with partners to develop so-called lithium-ion pumps. These are based on an electrode couple consisting of a lithium manganese oxide electrode (LMO electrode) and a nickel hexacyanoferrate counter-electrode (NiHCF electrode). When a voltage is applied, lithium is initially intercalated within the LMO electrode. When the voltage is reversed, potassium ions are intercalated within the NiHCF electrode, while the lithium ions are released and are concentrated in a recovery solution. We have developed different cell concepts with electrode areas from 7 cm² to 100 cm² and investigated them in a test rig that was constructed for this purpose. Now we are working on procedures and methods to produce and upscale electrodes for large module stacks.

The BrineMine project was funded by the German Federal Ministry for Education and Research (BMBF).



Test rig with a potentiostat to measure and characterize electrochemical cells for lithium extraction from brines.

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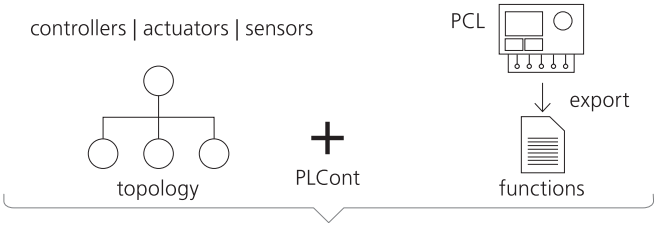
Digital Method to Completely Represent the Automation of Building Services

The planning, construction and operation of buildings is becoming increasingly digital. The rising complexity of buildings can thus be better represented, allowing the energy efficiency to be improved. One methodology to provide digitalized information on building services plants to all actors involved in the building is building information modeling (BIM). It allows access for different tasks at any time throughout all life-cycle phases of a building, for example for energy-related operation optimization of technical building plant. To achieve this, continuous and systematic connection of the technical building services, building automation and building operation is needed via BIM. In the "EnergieDigital" project, we have cooperated with RWTH Aachen and the Viega company to develop an integrated digital description of technical building services and demonstrated its application in a lighthouse project, the newly built seminar center, Viega World, in Attendorn, North Rhine-Westphalia, Germany.

At Fraunhofer ISE, our focus was on developing a method for complete, digital representation of the controls for technical building plant in BIM. The description of the technical building plant functions, which often exists in the form of paper today, is complemented by a digital model, which is enriched with updated information from the planning to the operation phases. The method encompasses the modeling of the controllers, sensors and actuators by semantic web technologies with existing ontologies and the PLCont ontology that we developed. Furthermore, the control functions that are implemented in programmable logic controller (PLC) are modeled digitally and according to a standardized protocol.



Digital representation of automation control topology connected with PLC functions

The PLCont ontology allows the control topology to be connected with PLC functions to obtain a complete, digital representation of the automation.

The digital representation of the automation allows the complete building services plant, including its controls, to be represented as part of the BIM model. In addition, users can access an "as programmed" representation of the functions outside the PLC, allowing planned and actually implemented controls to be compared. To this purpose, we have developed a prototypical graphical interface, in which the contents of the ontology-based description of the controls (digital system diagram, control parameters, function description and SPC code) are digitally modeled.

The Viega World seminar center was planned as a climate-neutral building and was taken into operation in January 2023. As part of the scientific monitoring, we control the targeted and actual performance of the seminar center. As an example, the team has already shown that the digital representation of the controls can simplify and accelerate certain processes of operation surveillance and energy-related optimization of operation.

The EnergieDigital project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

The climate-neutral Viega World seminar center in Attendorn, North Rhine-Westphalia, Germany.

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Extending the Application Range for Thermally Driven Adsorption Chillers

The cooling of buildings and processes already causes significant CO_2 emissions – and the demand for active cooling is rising. At present, primarily electrically driven, vapor compression refrigeration is applied. However, refrigerants with a high global warming potential (GWP) are often used there. The cooling sector is thus confronted by the challenges to switch to climate-friendly refrigerants and to reduce the electricity demand. At Fraunhofer ISE, we are addressing these challenges in several research projects.

Thermally driven cooling technologies (adsorption and absorption chillers) use waste heat or heat from renewable sources as the input energy instead of electricity and apply natural refrigerants such as water or ammonia (GWP = 0). In the SubSie research cluster, five consortia with partners from science and industry investigated how sorption systems with water as the refrigerant could address a wider application range, particularly for temperatures down to freezing point and below (SubSie platform).

At Fraunhofer ISE, we cooperated with the Fahrenheit company to develop adsorption chillers further ("SubSie-SubKon" project). In these systems, the refrigerant, water, is evaporated and adsorbed by a solid sorption agent such as silica gel or zeolite. The basic configuration of an adsorption chiller consists of three components: firstly, a heat exchanger called an adsorber, which adsorbs the refrigerant vapor from the evaporator in the adsorption half-cycle; secondly, the condenser, in which the desorbed water condenses, and thirdly, the evaporator, in which the cooling effect is achieved. In still simpler configurations, the same heat exchanger operates alternately as the condenser and the evaporator. The operation mode is then changed only by switching the temperature levels at the adsorber and evaporator/condenser. The choice of cycling time in operation allows optimization with respect to performance and efficiency (Coefficient of Performance, COP).

In investigations of innovative evaporators, we demonstrated that sublimation from a thin ice film can occur without damage to the heat exchanger and without significant reduction in the thermal performance of the evaporator.

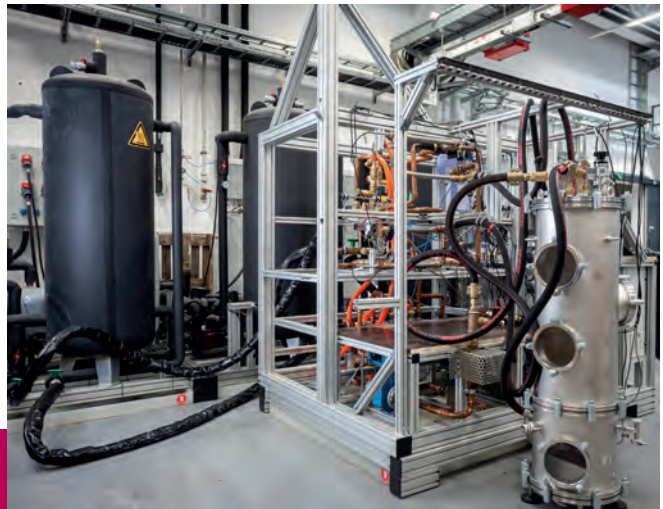
Complete adsorption modules were also investigated at refrigeration temperatures of below 3 °C. The water in the evaporator freezes occasionally under these operating conditions.

The cooling performance of the module at this operating point is reduced by about 30 %, for the same COP, compared to the operating point for an evaporator inlet temperature of 15 °C (refrigeration temperature: about 12 °C). For cycling times which lead to the same performance under both temperature conditions, the COP at the low temperatures is about 20 % lower.

At temperatures below 5 °C, applications e.g. in the food industry become accessible, which previously could not be addressed by adsorption chillers.

The SubSie research cluster was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Test rig to characterize adsorption heat pumps at Fraunhofer ISE.



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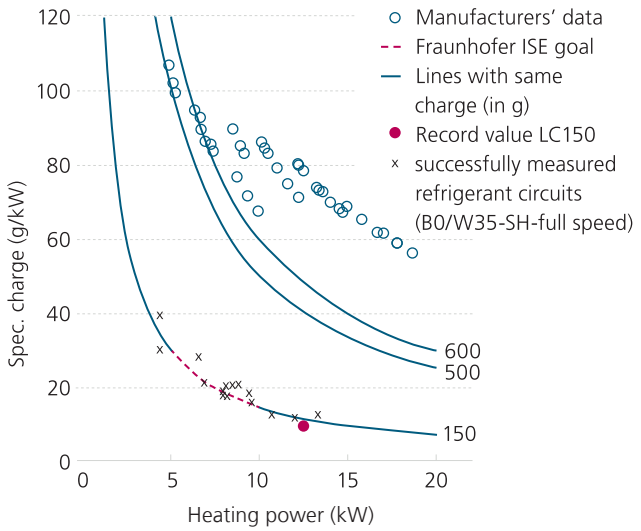
Developing Heat Pumps with Propane for the Market

For Germany to become climate-neutral by 2045, the building sector must make its contribution, as it is currently responsible for around 40 % of CO_2 emissions (including upstream processes). This could succeed with further installation of heat pumps, as they have a high potential to reduce CO_2 emissions in the provision of heat. The core component of heat pumps is the refrigerant circuit, where a refrigerant flows that evaporates at a low temperature. To generate heat, the fluid first absorbs heat from the surroundings; then the refrigerant is compressed as vapor in a compressor. The problem: At present, most heat pumps use refrigerants with fluorinated gases (F-gases) with a large global warming potential. The current version of the EU F-gas Regulation foresees a significant reduction in the use of substances with high global warming potential in the coming years. In addition, complete material groups should be incrementally forbidden due to their risk to humans and the environment. This increases the incentive to search for solutions with natural refrigerants.



The goal of the LC150 project was to achieve a heating power between five and ten kW with less than 150 g of propane. The project goal was surpassed.

Environmentally friendly alternatives are thus urgently required. One candidate is propane (R290), which is inexpensive and has a low global warming potential. In addition, propane has very good thermodynamic properties, which enable higher efficiency than heat pumps with conventional refrigerants. The challenge: propane is flammable. Thus, extensive safety measures apply for its use in heat pumps. If a heat pump in a single-family house, with its usual five to ten kW heating power, contains more than the prescribed maximum amount of 150 g of refrigerants, it can be installed only if stricter safety measures are taken. This could be changed by a new development at Fraunhofer ISE. In the "LC150" project, which has now been completed, we developed, together with a consortium of heat pump manufacturers, a propane refrigerant circuit with a reduced amount of refrigerant. A brine-based heat pump that was equipped with this circuit already achieves a heating power of around 12.8 kW with 124 g of propane, and could thus be installed inside houses without the need for additional safety measures. Only 10 g of propane are required per kW of heating power. That is a new record.

The seasonal coefficient of performance for the heat pump was determined by weighting data measured in the laboratory at different, characteristic operating points. It describes the ratio of the generated heat to the input electricity and attained a value of 4.7. Commercially available components were used for the prototype. An essential part of the concept is to consistently eliminate regions in the refrigerant circuit that do not contribute to the heat exchange or pressure adaptation. This made enormous reductions feasible in the amount of refrigerant used. Propane heat pumps should also be used in apartment buildings. In the new "LCR290" project, we plan to develop simply applicable and reproducible heat pump solutions to replace gas and oil heating in apartment blocks. Again, propane will be used as the refrigerant, the amounts of refrigerant will be reduced to a minimum and new safety concepts will be developed for the remaining quantity of propane. A project consortium with companies from the heating and housing sectors has been founded to ensure practically relevant and rapid implementation.

The LC150 project was and the LCR290 project is being funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

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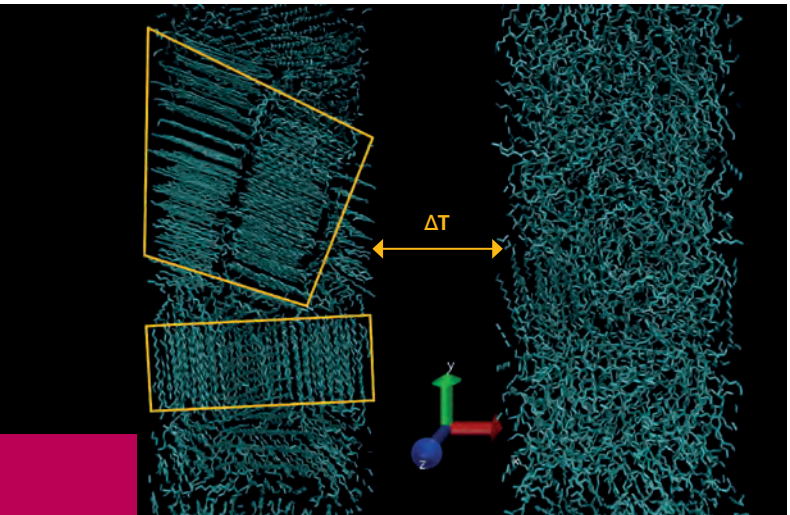
Efficient Decarbonization of Heating and Cooling by Innovative Thermal Storage

Thermal energy storage is becoming increasingly relevant to ensure heating and cooling as required, as part of the expansion of energy supplies from renewable sources and to promote flexibility and sector coupling. Innovative approaches to reduce costs are needed to support the dissemination of storage systems. One possibility is to replace some of the expensive fluids used in high-temperature storage tanks by inexpensive filler materials. In the "FENOPTHES" project, we have further pursued this approach and extended the existing test rig for molten salt storage by an additional storage tank. Into this tank, we introduced loose filler materials (photo, right), which consist of different, heat-resistant materials (e.g., cinders) that are also stable at high temperatures due to a binder containing phosphate. These materials are in direct contact with a molten salt mixture of 60 % sodium nitrate ($NaNO_3$) and 40 % potassium nitrate (KNO_3). The working temperatures usually lie between 290 °C and 550 °C. The charging and discharging of the system were investigated for different mass flows and temperatures. In cycling operation, a promising storage efficiency of 98 % and a utilization rate of 73 % were achieved. Altogether, the project results show that molten salt storage with filler materials represents an economically interesting solution for process heat in industry.

Molten salt / loose filler material storage tank after introduction of filler material.

Beyond this, we at Fraunhofer ISE also see potential for the isothermal phase transition of phase change thermal materials (PCM) to realize compact storage units with a large capacity and small temperature differentials in the low-temperature range between 0 °C and 100 °C. Often, the material properties of the PCM in its solid state impose limits, for example with regard to the heat transfer performance. If the PCM is dispersed in a liquid, it can still be pumped in the crystallized state and thus overcomes this limitation. We are therefore developing PCM slurries (PCS) as a technology for thermal storage. Due to their high heat capacity, they can be used simultaneously as heat storage materials and heat transfer fluids. If PCS are supercooled, the melting and crystallization temperatures differ from each other. In the "MINAKRIP" project, seed materials to reduce supercooling were investigated experimentally and by molecular-dynamic simulations. The simulations allow the formation of crystals and the effect of the crystallization seeds to be understood better at an atomic level (illustration below). An optimized seed material reduced the supercooling of a paraffin-water emulsion by 9 K. Building on these results, in future it will be possible to develop PCM slurries with a narrow temperature range, that can thus be used for numerous further applications.

The FENOPTHES and MINAKRIP projects were funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).



Phase transition of PCM molecules between the solid (left) and liquid states (right) in a molecular-dynamic simulation. Within yellow frame: PCM crystallites.

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Field Measurements to Evaluate the Efficiency and Acoustic Emissions of Heat Pumps in Existing Single-Family Houses

Heat pumps play an important role in the sustainable transformation of the building sector. However, this transformation can only be implemented if heat pumps are also introduced on a large scale into the existing building stock. This is accompanied by various challenges – such as access to suitable heat sources and the higher temperatures that are needed to heat the buildings.

Historical single-family house with an outdoor air heat pump.

Outdoor air heat pump with additional acoustic measurement technology in front of a single-family house from 1955.

Together with nine heat pump manufacturers and two energy utilities, we are addressing several research questions about applying heat pumps in existing seasonal performance factor in the "HP-QA in Existing Buildings" project, which is running until the end of 2024. To demonstrate the state of the art and derive optimization opportunities, up to 75 heat pumps are to be experimentally monitored in buildings dating from 1826 to 2001, and the data will be analyzed with respect to efficiency and operating behavior. Further important topics are the measurement of acoustic emissions by outdoor air heat pumps and investigations of bivalent systems and self-consumption of PV electricity.

The first interim results of the efficiency analysis refer to the measurement period from February 2022 to January 2023. The 21 outdoor air heat pumps that were evaluated during this period achieved a seasonal performance factor (combined generation efficiency for space heating and domestic hot water) of 3.3, with a bandwidth from 2.4 to 4.1. The seasonal performance factor for the eight ground-source heat pumps that are equipped with geothermal probes ranged from 3.6 to 5.4. Compared to a gas-fired boiler as the reference heat generator, the savings in greenhouse gas emissions were between 18 % and 64 %, based on the lowest and highest aseasonal performance factors. In 2030, after about half the usual service lifetime for these heat pumps, the savings would be between 58 % and 81 % or 77 % and 90 %, depending on the assumption made for the expansion rate of electricity generated from renewable sources.

The interim results from the efficiency analysis already demonstrate the ecological advantages of heat pumps compared to fossil-fueled boilers. The goal now is to further expand the data base, to analyze the acoustic measurements in detail and to derive quality-control measures to ensure efficient operation of heat pumps, based on deeper analyses of the operating data. In this way, our research can make an essential contribution to the rapid introduction of efficiently operated heat pumps in the addressed application area.

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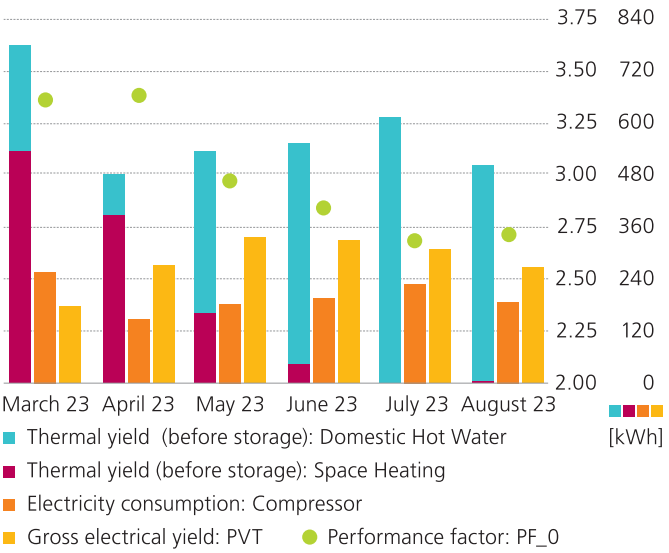
Photovoltaic-Thermal Collectors – New Product Solutions for a Growing Market

Photovoltaic-thermal collectors (PVT collectors) simultaneously generate electricity and heat from solar energy. Combined with a heat pump, these systems can be used to supply space heating and domestic hot water efficiently and with only low CO_2 emissions. They are thus an important component of our research at Fraunhofer ISE on the route to the energy transition. Compared to heat pumps with an outdoor air unit, PVT collectors have the advantage that they do not cause any acoustic emissions, they use the generated electricity themselves and potentially can operate more efficiently due to the source temperatures that have been raised by the input of solar energy.

In the accredited TestLabs, PV Modules and Solar Thermal Systems, we at Fraunhofer ISE have comprehensively characterized PVT collectors that we have developed and produced, together with our industrial partners, within joint research projects. Commercial products and prototypes from different manufacturers have also been tested in the laboratory. Our methodological approaches and laboratory facilities proved to be robust for this application.

Thanks to our industrially relevant research, at Fraunhofer ISE we have established a prominent position in accompanying PVT new developments from prototypes up to market introduction. Thus, our services are in strong demand to characterize modules during a development process and also to test PVT modules to qualify them for market introduction. The increasing relevance of PVT collectors for building energy supplies is indicated by the inclusion of further PVT demonstration systems within the energy monitoring program of the currently running "integraTE" project. The information about system behavior and energy flows can be accessed by our customers online. This ensures high transparency about the system efficiency and yields, which are important for technology evaluation during an early phase in market entry (see graph).



Thermal yields for domestic hot water and space heating, electrical yields and electricity consumption of the heat pump compressors, as well as monthly average performance factors PF_0 for a PVT system with covered PVT collectors. Some of the electricity generated by the PVT collectors can be used directly to drive the heat pump. The thermal yields are measured at a balance measurement point between the heat pump and the thermal storage tank and allocated to space heating or domestic hot water during the data processing. The PF_0 takes only the power drawn by the compressor into account for the electricity balance.

We made an important contribution to the training of tradespeople in the building sector by holding lectures and training courses, e.g., in the ongoing education programs for energy advisors and the relevant building trades.

The integraTE project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Covered PVT collector with a low-e-coated glass cover during the performance test on the outdoor test facility of TestLab Solar Thermal Systems at Fraunhofer ISE.

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Standardized BIPV Façade Elements with Integrated Power Electronics

Demonstrator at Fraunhofer ISE. Upper two rows: BIPV modules with crystalline silicon; center two rows with patterns: modules with organic PV; the lower three rows originate from the preceding project.

Building roofs and façades are excellently suited for the integration of photovoltaics (building-integrated photovoltaics, BIPV). The potential area even exceeds the demand of the energy transition, they are close to the point of consumption and they can be used without sealing further land areas. However, the current expansion rate is too low to contribute significantly to the success of the energy transition.

The Standard-BIPV-System project aims to facilitate the application of façade BIPV and thus to accelerate its dissemination. The focus is particularly on the existing building stock. The project is being carried out by Fraunhofer ISE in cooperation with six partners from industry and research.

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Conventional, commercially available PV modules for roof-attached systems are seldom compatible with the dimensions required in the building stock and they usually do not meet the building code requirements for façades. Above all, the time and effort to plan and install BIPV façade solutions have been major barriers up to now. Important aspects here include the electrical connection of the modules and tolerance to (partial) shading. The project addresses these challenges by the development of a BIPV façade solution, in which the dimensions of the modules have been reduced, on the one hand, such that they match the requirements better. On the other hand, the electrical complexity is reduced by connecting two or four BIPV modules to a module inverter to form an electrical unit. The unit is connected directly to the AC circuit of the building. This modular approach makes it simpler to plan and install the PV system and often there is no need for elaborate radiation and shading simulations.

The modules have an area of 1 m x 1.2 m and consist of PV cells of either crystalline silicon or organic PV. Steel cassettes and mineral fiber panels were investigated as substrates, both being materials that are well known and proven in façade construction. The front surface of the PV cells is protected by a glass cover. The choice of materials makes architecturally high-quality, frameless modules feasible. Well-established façade solutions were used for the sub-structure. In this way, the solar system can be integrated into a conventional façade, the effort to obtain a building permit is reduced and the additional, PV-specific effort for mounting decreases. Specifically developed, four-pole solar cables with a plug were used for the electrical connection. They allow the bypass diodes to be shifted away from the modules into the ventilated space behind the rear-ventilated rainscreen façade, reducing their temperature and combining the power electronics with the inverter.

We have tested the applicability of the concept with both a mobile demonstrator and also a full-scale façade of an existing building at Fraunhofer ISE. Feedback on the demonstrator and also the experience gained with the existing façade show that the basic idea is viable. Further potential for improvement and solutions were identified and will be investigated in follow-up projects.

The Standard-BIPV-System project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

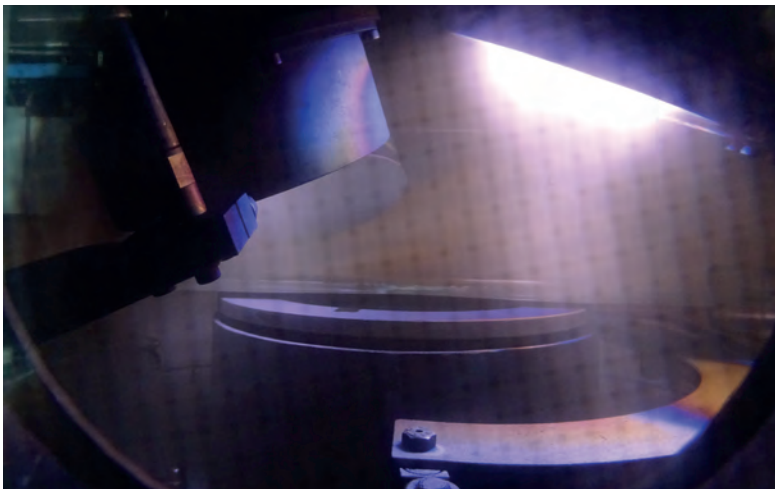
Corrosion Barrier Layers for Bipolar Plates and Porous Transport Layers in PEM Electrolysers

Strongly corrosive conditions occur on the anode side of a polymer electrolyte membrane (PEM) electrolyser. For this reason, the incorporated bipolar plates (BPP) and the porous transport layers (PTL) are usually constructed of titanium. Titanium ensures that the component is highly resistant against corrosion. However, the resulting passivation layer leads to contact resistance that reduces the performance of the electrolysis cell. Thus, platinum is frequently applied as a corrosion-protective layer, which keeps the contact resistance low. At present, this coating is expensive due to the high material costs and a production process that has not been optimized.

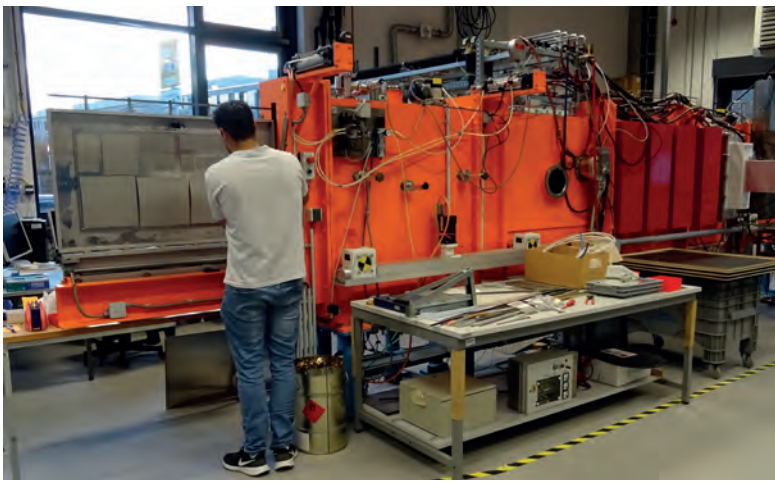
Within the "H2Giga HyThroughGen" project, we are conducting research on inexpensive alternative materials. One approach is the use of mixtures of noble and base metals. To facilitate this, we have developed a procedure which allows quick screening of material mixtures. This is done by co-sputtering: simultaneous sputtering from two sputtering sources onto a titanium substrate (upper photo). This results in a coating with a gradient in its composition along the substrate. Subsequently, this substrate can be anodically oxidized in a single step, and both the composition and the contact resistance can be determined as a function of the position on the substrate. The anodic oxidation reproduces the corrosive conditions in the electrolysis cell.

Our preliminary results already show that addition of 50 % of the base metal led to the same contact resistance after anodic oxidation as for the pure noble metal. As a consequence, half of the noble metal could be saved. We are currently investigating further material mixtures, including materials without noble metals.

In addition to the material composition, we are also optimizing the coating process. Within the "H2Giga PEP.IN" project, we are studying the processing chain, starting with the substrate cleaning by treatment of the substrate with a linear argon ion beam immediately before the coating and the coating process. The results to date have indicated in detail which processing parameters are particularly relevant and suggest how the processing times can be significantly shortened. In addition, we are developing methods for process control and quality assurance. In particular, we are working on ex situ corrosion tests for coated BPPs and PTLs both for fuel cells and for PEM electrolysers.



Production of gradient layer mixtures by co-sputtering.



Preparation for PTL coating in the sputtering equipment.

The HyThroughGen and PEP.IN projects are funded by the German Federal Ministry for Education and Research (BMBF).

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A National Hydrogen Strategy for the United Arab Emirates

Skyline of Abu Dhabi, United Arab Emirates.

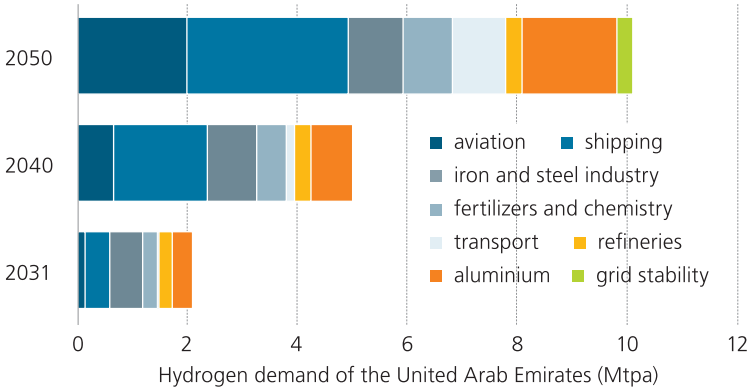
The United Arab Emirates (UAE) have developed a national hydrogen strategy with which they are pursuing two essential goals: On the one hand, to count among the largest low-carbon hydrogen producers in the world by 2031, and on the other hand, to advance the decarbonization of local industry by 2050 with the support of the hydrogen industry. The government of the UAE entrusted the consultants, GHD Advisory, and the Fraunhofer Cluster of Excellence Integrated Energy Systems (CINES), to which Fraunhofer ISE also belongs, with the preparation of this study.

The UAE will primarily use hydrogen to decarbonize the local industry – however, the global export market will also be expanded in parallel. The UAE will establish hydrogen hubs ("H_2 Oases") as a practical approach to accelerate industrial adoption of hydrogen, cultivate a supply chain, and enable infrastructure. In addition, investments are being made in research and development which support the expansion of the hydrogen value chain.

That the local demand for hydrogen will be substantial (graph below) is one of the results of the strategy process, in which all of the important hydrogen and energy stakeholders in the country were involved. Driven on by the net-zero goal for 2050 as well as the global demand for products like "green" steel, sustainable fuels for aviation and the decarbonization of industrial sectors that are difficult to electrify, the UAE can proceed with the development of projects, as they – unlike other countries – do not first need to establish a market for their product.

The measures proposed in the strategy have the goal of producing 1.4 million metric tons of low-carbon hydrogen annually by 2031, distributed over different production routes. At the same time, investments should be made in hydrogen research and development. For the years after 2031 and along the path to a decarbonized future, Fraunhofer CINES estimates that the production capacity of low-carbon hydrogen of the UAE could amount to 7.5 million metric tons per year by 2040 and almost 15 million metric tons per year by 2050.

In addition to the expected high local demand for hydrogen, the team of authors of the strategy concludes that the UAE has a very good starting point for exports: The country is located in an advantageous geographical position to deliver to important markets in Europa and Asia, and is equipped with the corresponding export infrastructure and harbors. Thanks to large reserves of natural resources, high capacity for renewable energy, an international trade and financial center and a qualified and innovative labor force, the UAE are well prepared for growth in the low-carbon hydrogen industry and for export.



Sector-specific demand for low-carbon hydrogen in the UAE from 2031 to 2050.

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Along-the-Channel PEM Electrolysis Cell for Spatially Resolved Investigation of Mass Transport Effects

Large-area polymer electrolyte membrane (PEM) electrolysers with membrane areas of several 1000 cm^2 pose high demands on the water and thermal management in the electrolysis cell. Inhomogeneous conditions are particularly evident along the channel (AtC) with regard to the consumed water and the generated gases, hydrogen and oxygen. At Fraunhofer ISE, we have developed a segmented AtC PEM electrolysis test cell to conduct spatially resolved investigations of these so-called mass transport phenomena.

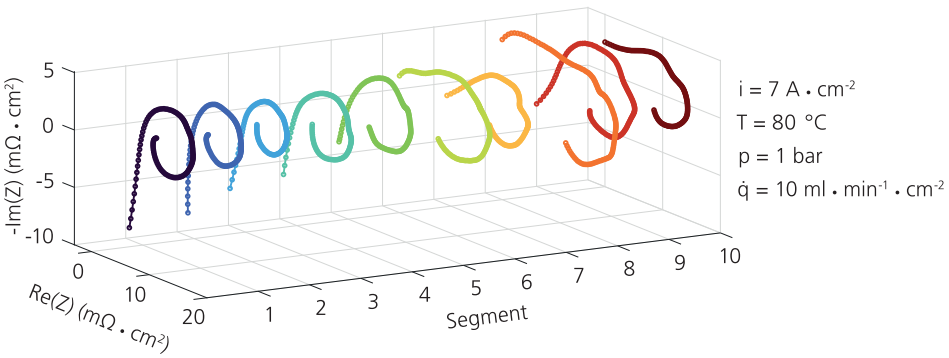
Segmented along-the-channel test cell to analyze local mass transport processes.

The AtC cell was developed and investigated within the "StacIE" project. The partners involved in this project are researching the scale-up and industrialization of PEM electrolysis. The project is focusing on the further development of stack technology for large-volume production capacities.

To analyze the mass transport along the flow channel of a PEM electrolysis cell on an industrially relevant scale, we constructed an AtC laboratory cell with a length of 30 cm and a width of 2 cm. The generated hydrogen and thus also the water consumption correlate with the applied current density. To create the most demanding conditions possible, we dimensioned the cell for a current density of up to 600 A (10 A/cm^2) and tested it successfully. We will thus be able to use the cell to analyze operating points that are anticipated in future with very high hydrogen generation rates. The cell is suitable for investigations at temperatures up to 80 °C and a differential pressure up to 10 bar. With the help of a specially conceived measurement circuit board, measurements of the current density and temperature distributions can be made with 120 measurement contacts. In addition, the cell is divided along the parallel channel structure by separation of the electrical contact into ten segments. Electrochemical impedance spectra (EIS) can be recorded in each of the segments and additionally over the complete laboratory cell. To separate the processes in the two half-cells, three reference electrodes are positioned at the inlet, in the center and at the outlet of the cell, with which the membrane potential can be determined. For this work, EIS is the appropriate measurement methodology to separate the polarization processes such as the mass transport processes.

In the further course of the projects, materials will be characterized in the AtC cell which will also be used in future StacIE stack platforms. We aim to gain insight into the internal processes along the flow channel thereby. Furthermore, we want to understand the influence of different structural parameters of porous transport layers on local polarization processes.

Local electrochemical impedance spectra (EIS) to analyze the mass transport along the cell segments.



The StacIE project is funded as part of the H2Giga lighthouse project by the German Federal Ministry for Education and Research (BMBF).

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Dimethyl Ether as a Global Hydrogen Carrier

Green, hydrogen-based molecules play a key role in the decarbonization of the global energy system. According to current prognoses, twelve million metric tons of hydrogen should be traded by 2030. One open question is still the transport of hydrogen over long distances (longer than 6000 km, e.g. from Perth or Cape Town to Rotterdam), as hydrogen pipelines cannot be used there. Even after energy-intensive compression or liquefaction by cooling, the volumetric energy density of hydrogen is low and the transport infrastructure does not yet exist.

Fraunhofer ISE has identified the potential of dimethyl ether (DME) as a promising, environmentally friendly hydrogen carrier within the framework of a closed carbon cycle. The DME is synthesized from CO_2 and hydrogen from renewable energy sources and transported by ship to the energy-importing country. There, hydrogen can be generated by thermochemical reforming processes from the DME, and then fed into gas networks and pipelines. Carbon dioxide is created as a by-product, which is then transported in liquid form in the same ship back to the synthesis location and serves as a raw material for synthesis. A closed CO_2 cycle is thus established.

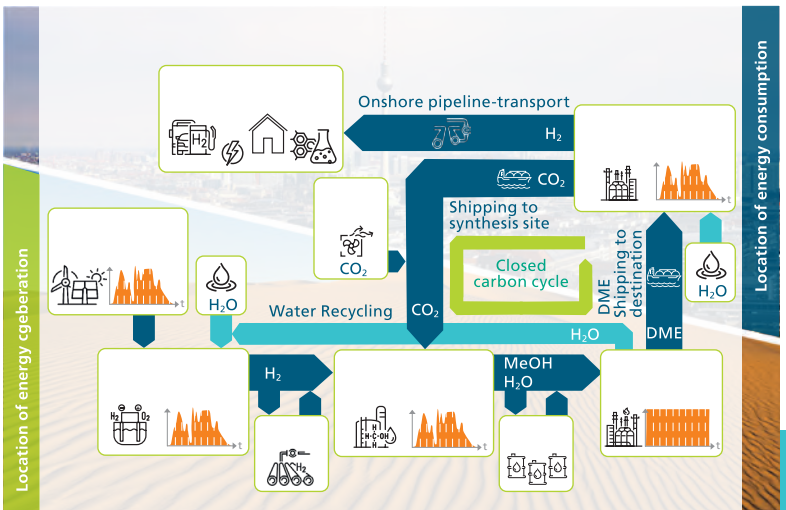
In comparison to alternative hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHC), DME offers a larger technical hydrogen storage capacity. As a result, the shipping volume and thus the transport costs can be reduced. Furthermore, the water which is formed as a by-product during the DME synthesis can be used for the electrolysis. Compared to the production and transport of cryogenic hydrogen, the water demand can be halved in this way, which often represents a significant advantage in sunbelt regions that are frequently subject to water scarcity. In addition to the application as a hydrogen carrier, DME is also an excellent fuel and can also be used as a basis to product sustainable aviation fuels. We are investigating this process in detail within the "SAFari" project.

To increase the efficiency of the processes, the INDIGO technology, for which Fraunhofer ISE has lodged a patent claim, should be applied to produce DME. The process simplifies the conventional production process by applying the reactive distillation concept under mild reaction conditions and the usage of alternative catalysts.

Thermochemical hydrogen production from DME takes place at moderate temperatures compared to fossil-based energy sources such as natural gas or crude oil fractions. Furthermore, the heat demand of the catalytic, endothermic reforming reaction step is 25 % lower. In order to provide commercial DME reforming plants, process steps such as catalysis, heat generation from low-CO_2 sources (e.g. electricity and industrial residual heat), hydrogen-CO_2 separation processes and the evaporation of water and DME must be adapted. Therefore, we are carrying out experimental and theoretical research on these subjects at Fraunhofer ISE within the "Power-to-MeDME" project.

The SAFari project is funded by the German Federal Ministry for Digital and Transport (BMDV). The Power-to-MeDME project is funded by the German Federal Ministry for Education and Research (BMBF).

Closed carbon cycle with synthesis of dimethyl ether (DME) in the exporting country and DME reforming in importing country.



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Performance and Lifetime of Fuel Cells after Use of Contaminated Hydrogen

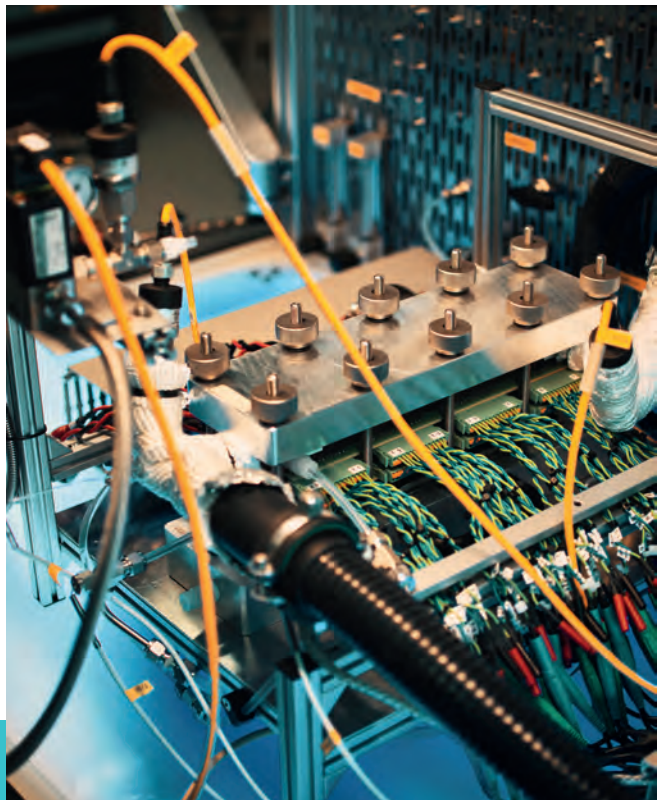
Depending on the production and transport processes, hydrogen for Fuel Cell Electric Vehicles (FCEVs) contains impurities such as hydrocarbons which affect the efficiency and lifetime of fuel cells. The standard on hydrogen quality, ISO 14687-2, thus contains specifications of the maximum permissible concentrations of corresponding contaminants. These maximum values are determined in comprehensive tests and are incorporated in mandatory, national regulations for hydrogen filling stations. If the demands on the hydrogen purity are high, the levelized costs of hydrogen generation increase and thus the operating costs of FCEVs. By contrast, if the demands are low and the concentration of contaminants high, irreversible damage to the fuel cell could occur in the worst cases.

In the "H2Fuel" project, we are conducting pre-normative research on contaminated hydrogen in current and future fuel cell configurations in order to justify possible amendments to ISO 14687-2. Operation data of FCEVs show that frequent load changes – which can be simulated, e.g., by the so-called Fuel Cell Dynamic Load Cycle – and the duration between stopping and starting a FCEV can support regeneration after contamination. For example, longer breaks between driving phases, e.g., overnight after parking the vehicle, can contribute to fuel cell recovery after strong contamination with carbon monoxide.

This occurs when the system cools down to ambient temperature and water condenses or gas diffuses between the electrodes: The catalyst poison can then oxidize at the affected electrode. In turn, this effect, combined with operating modes which are adapted to contaminated hydrogen, could justify relaxation of the maximum values for contaminant concentration.

For economic reasons, however, fuel cell manufacturers often have the goal of reducing the amount of platinum per stack in the fuel cells, which can negatively affect the tolerance of the system to contaminants. Efficiency losses and irreversible damage to the electrodes appear more frequently if only a small buffer against the loss of active catalyst surface is available. It is thus important to limit the concentration of each type of hydrogen contaminant to such a low level that irreversible degradation does not occur.

In our experimental series, we identified groups of contaminants which caused such unexpected, irreversible degradation effects. With adapted experimental protocols and cell designs for spatially resolved tests, we investigated the operating modes which reinforce contamination-induced degradation, in order to localize this damage more accurately at the fuel cell level.



Cell platform for spatially resolved measurements.

The H2Fuel project was funded by the German Federal Ministry for Digital and Transport (BMDV).

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Transformation Paths toward Decarbonization of the Heating Sector: a Bottom-up Approach

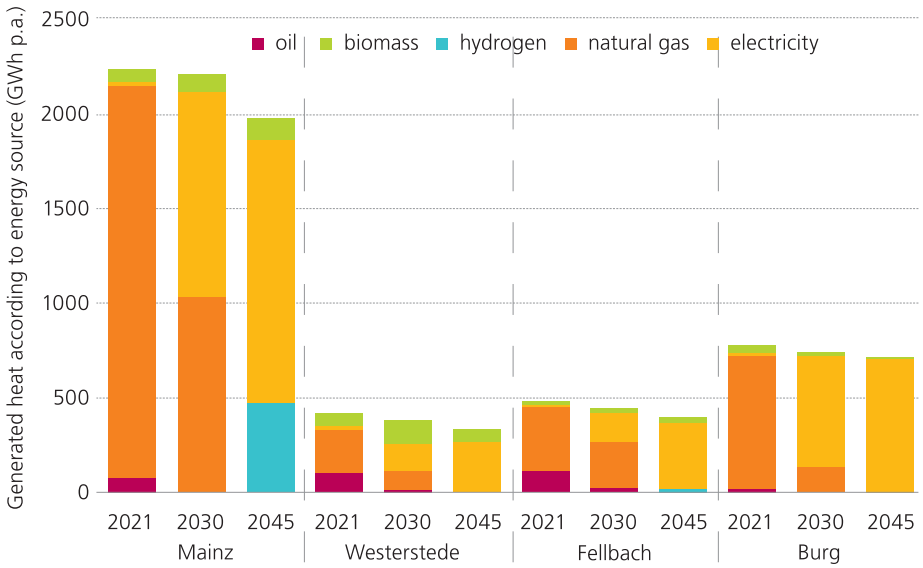
Which role will hydrogen play for future energy supply? Will we heat with hydrogen? If so, can this reduce the need to expand the electricity distribution grids? And will municipal heating planning advance the decarbonization of the heating sector? These and associated questions were answered by researchers from Fraunhofer ISE and Fraunhofer IEE in a study commissioned by the German National Hydrogen Council. In doing so, they chose a bottom-up approach for the first time, in which they modeled four supply areas in detail, namely Burg near Magdeburg, Fellbach, Mainz and Westerstede.

For each of the four case studies, prevailing conditions were taken into account, such as the existing building stock, electricity, gas and heating grids, current electricity and gas consumption, existing power stations and areas and potential for photovoltaics, solar thermal and geothermal systems as well as heat sources and their potential for (large) heat pumps. We applied the regional, inter-sectoral energy system model, DISTRICT, of Fraunhofer ISE to model five scenarios for each of the four case studies. Each scenario assumes that the climate goals will be reached and depends on variables such as price developments, availability of technology, infrastructure, the local situation of relevant trades and renovation rates.

Across all of the scenarios, it became evident that the expansion of heat pump installations is the most promising strategy to decarbonize space heating. In particular, heat pumps represent the only available option to achieve the publicized climate goals for 2030. Also for the period after 2030, they present the best solution for distributed space heating supply in every scenario.

In the district heating and process heat sectors, the scenarios support the conclusion that a mix of large heat pumps using different heat sources, hydrogen-driven combined heat and power and further renewable technologies such as thermal use of solar energy, geothermal systems and biomass will become established. The selection of technology depends strongly on the heat sources that are locally available. The potential of hydrogen as an energy source was evident primarily for district heating and process heat in all scenarios.

The analysis of the local networks revealed that the demand for electricity will increase significantly in all the investigated scenarios and regions and that expansion of the electricity grid is necessary, regardless of the share of hydrogen use in the building sector. The modeling chain of Fraunhofer ISE and Fraunhofer IEE was able to answer diverse questions at different levels of detail and thus make an appreciable contribution to the debate about decarbonization of the heating sector. The demand analysis of the four selected towns and cities revealed how complex the transformation of the heating sector is in the specific urban context and local environment. In addition, it illustrated the need for integrated energy planning guidance to initiate decarbonization across all sectors and grids.



Transformation of heat generation in the four studied regions for the electrification scenario (scenario 2 in the study), classified according to energy source.

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Joint Building Electricity Supplies: Comparison of the Economic Viability of On-Site Systems

For the residents of the 21 million apartment buildings in Germany, active participation in the energy transition is possible only to a limited degree. The Federal Government aims to change this situation and proposes a model to supply photovoltaic electricity more simply to apartment buildings: In the "joint building electricity supply" model (gemeinschaftliche Gebäudeversorgung GG), PV electricity from roof-mounted systems can be supplied directly to the tenants of an apartment building. The generated PV electricity is distributed according to an agreed allocation key. Each tenant makes an individual electricity contract with an energy utility for the remaining electricity supply. In contrast to the "tenant electricity model" (Mieterstrommodell), the owner of the PV system is not required to supply enough electricity to cover a tenant's complete consumption. The new regulation promises to operate with less bureaucratic effort.

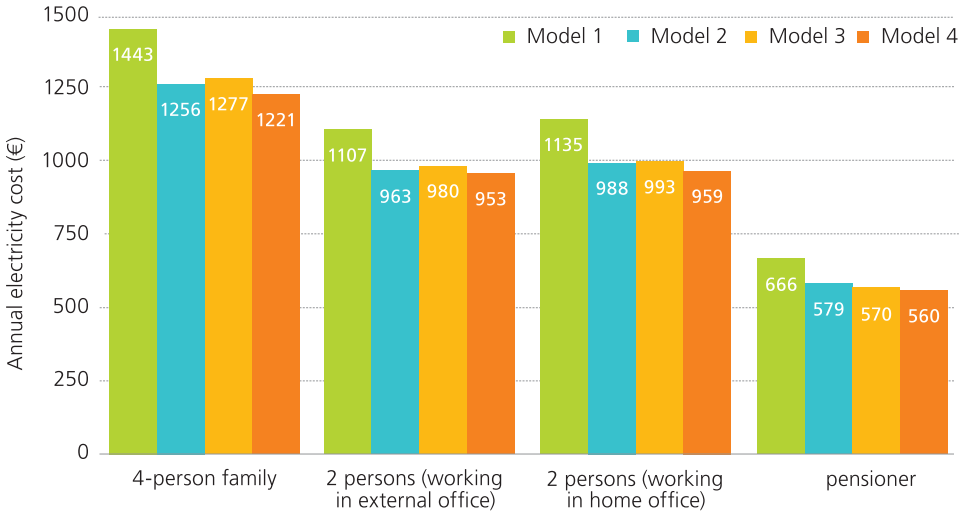
In a case study for an apartment building with four apartments, we at Fraunhofer ISE have investigated four electricity supply models with respect to their economic viability:

1. Complete feed-in: the owner of the PV system feeds all of the generated electricity into the grid; the tenants obtain their electricity from a utility.
2. Tenant electricity: the PV system owner sells electricity to the tenants.
3. Static joint building electricity supply: the PV system owner rents system shares to the tenants (fixed allocation of the PV electricity).
4. Dynamic joint building electricity supply: the PV system owner rents system shares to tenants (allocation of PV electricity according to individual consumption).

From the perspective of the PV system operator, all models are economically viable – the least bureaucratic effort is caused by complete feed-in. To make the desired transition away from complete feed-in attractive to the operator, we calculated economic viability for the following assumptions: Profit increase of 15 % for the PV system owner for all three alternative models (2, 3 and 4) compared to complete feed-in (1). Under this assumption, the residents have a price advantage for all three alternative models compared to purchasing all electricity from a utility. The annual costs for the residents differ only slightly between the tenant electricity and joint building electricity supply models. The most favorable conditions are achieved by the dynamic joint building electricity supply model, as here the dynamic allocation ensures maximum self-consumption and the additional costs for accounting and sales of the tenant electricity model do not occur.

The annual simulation is based on load profiles which we generated at Fraunhofer ISE using the SynPRO analytic tool. Overall, the investigation showed that the joint building electricity supply model is a promising concept to actively include apartment tenants in the use of self-generated PV electricity. The model is financially attractive for all parties and can help to reach the stated PV expansion goals.

Annual electricity costs in an apartment building with four tenant parties: a family of four, two office workers (full-time in an external office), two office workers (in home office) and a pensioner. The four models (1 to 4) assumed are as described in the main text.



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Decarbonization of the Energy Supply for Real Estate Property

A decarbonized energy supply is becoming increasingly important for commercial enterprises – not only in the context of rising energy prices and supply shortages. Businesses can move toward climate neutrality by determining and controlling their energy consumption and emissions and by taking specific measures to reduce emissions.

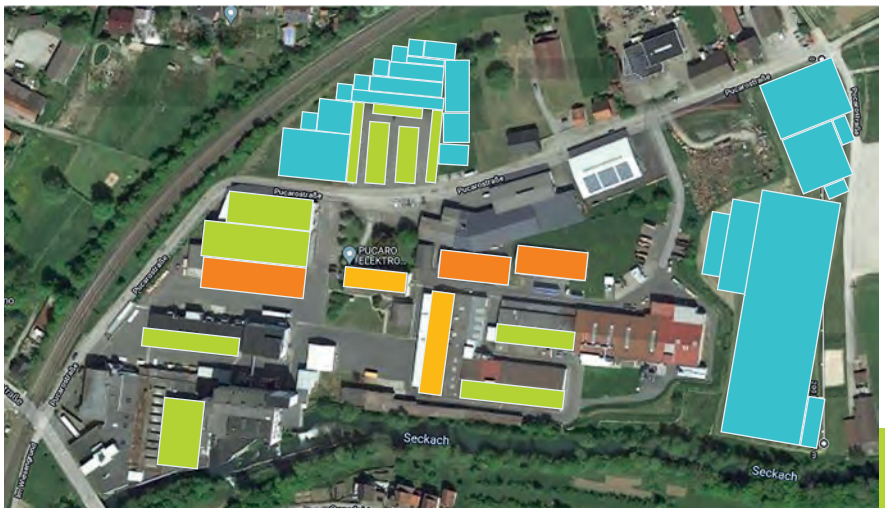
Today, there are many standards to develop, achieve and monitor decarbonization goals. On contract to the German Environment Agency (UBA), we have investigated and analyzed these standards. In doing so, we prepare essential components for credible climate targets in the short-term, medium-term and long-term perspectives and for a comprehensive emissions balance for commercial enterprises. Compensation of emissions should always be the last choice to achieve decarbonization goals. For the energy supply sector, it is advisable to develop transformation routes that allow intermediate goals to be identified and thus provide decision bases for restructuring the energy system.

Overall, the completed projects reveal very different demands on the energy supply for industrial and commercial real estate. To evaluate these and identify the options for sustainable reorganization, the first step is to record the current consumption, demands and generation potentials on site. In addition to the absolute consumption values, we identify the required temperatures for providing heating and cooling. Also, the required peak power and options to use waste heat are included when determining the status quo. Different tools are applied during this process – for example, the waste heat potential of industrial and commercial units is determined using pinch analysis. The existing potential to generate electricity and heat on site from renewable energy sources is also determined. On this basis, different transformation routes are developed which depend on the scenarios that are assumed for the energy price development and other boundary conditions. For process heat, the choice of supply technology depends strongly on the required temperature level. For temperatures below 200 °C, for example, high-temperature heat pumps are an option. If higher temperatures are required, there are the options for direct electrification or a switch to CO_2-free fuels such as hydrogen or synthetic gases.

Our case studies, including those on the property of PUCARO Elektro-Isolierstoffe GmbH in Roigheim, show that the potential for generating photovoltaic electricity must be exploited as early as possible. On the long term, the heat supply must also be completely rebuilt to achieve decarbonization. In order to meet their remaining electricity demand, enterprises can temporarily resort to power purchase agreements. Overall, the comparison of possible transformation routes represents a good method to make price risks and their effects on investment decisions visible.

Potential PV installation areas at the Roigheim site of PUCARO Elektro-Isolierstoffe GmbH. Photo source: Google, Bilder © 2023 AeroWest,GeoBasis-DE/BKG, Maxar Technologies, map data © 2023 GeoBasis-DE/BKG (©2009).

- Roof-installed PV system
- Ground-mounted PV system
- Overhead PV system
- Already installed PV system



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Events in 2024 with Participation of Fraunhofer ISE

January

Batterieforum Deutschland	Berlin, Germany	24.–26.01.2024
SPIE Photonics West	San Francisco, USA	27.01.–01.02.2024

February

e-world Energy & Water	Essen, Germany	20.–22.02.2024
World Hydrogen MENA	Dubai, United Arab Emirates	26.–29.02.2024
39th PV-Symposium	Bad Staffelstein, Germany	27.–29.02.2024

March

LOPEC	Neuchâtel, Switzerland	05.–07.03.2024
PVinMotion	Munich, Germany	06.–08.03.2024
International Battery Seminar	Orlando, USA	12.–15.03.2024

April

SiliconPV	Chambéry, France	15.–19.04.2024
Berliner ENERGIETAGE	Online	16.–18.04.2024
CO_2-based Fuels and Chemicals Conference	Cologne, Germany	17.–18.04.2024
Hannover Messe	Hanover, Germany	22.–26.04.2024
OWPT Conference	Yokohama, Japan	23.–26.04.2024

May

World Hydrogen Summit & Exhibition	Rotterdam, Netherlands	13.–15.05.2024
HOPV24	Valencia, Spain	13.–15.05.2024
34th Symposium Solarthermie und Innovative Wärmesysteme	Bad Staffelstein, Germany	14.–16.05.2024
Berliner ENERGIETAGE	Berlin, Germany	15.–16.05.2024
EMRS Spring Meeting	Strasbourg, France	27.–31.05.2024
14th IIR Conference on Phase-Change Materials and Slurries for Refrigeration and Air Conditioning	Paris, France	29.–31.05.2024

June

Enerstock	Lyon, France	05.–07.06.2024
4th Terawatt Workshop	Asilomar CA, USA	06.–08.06.2024
52nd IEEE Photovoltaic Specialists Conference	Seattle, USA	09.–14.06.2024
ACHEMA	Frankfurt am Main, Germany	10.–14.06.2024
AgriVoltaics	Denver, USA	11.–13.06.2024
PCIM Europe	Nuremberg, Germany	11.–13.06.2024
SNEC Photovoltaic Power Conference & Exhibition	Shanghai, China	11.–15.06.2024
The Battery Show Europe	Stuttgart, Germany	18.–20.06.2024
The smarter E Europe	Munich, Germany	18.–21.06.2024
42nd International Energy Workshop	Bonn, Germany	26.–28.06.2024
tandemPV Workshop	Amsterdam, Netherlands	26.–27.06.2024

September

5th International Conference on Solar Technologies & Hybrid Mini Grids	Palma de Mallorca, Spain	04.–06.09.2024
PSCO	Oxford, United Kingdom	16.–18.09.2024
EU PVSEC	Vienna, Austria	23.–27.09.2024
EUMETSAT Meteorological Satellite Conference	Würzburg, Germany	30.09.–04.10.2024

October

FVEE Jahrestagung	Berlin, Germany	08.–09.10.2024
hy-fcell	Stuttgart, Germany	08.–09.10.2024
Chillventa	Nuremberg, Germany	08.–10.10.2024
SolarPACES	Rome, Italy	08.–11.10.2024
eMove360° Europe	Munich, Germany	15.–17.10.2024
11th Solarbranchentag Stuttgart	Stuttgart, Germany	17.10.2024
Glasstec	Düsseldorf, Germany	22.–25.10.2024

November

PVSEC-35	Numazu (Mt. Fuji), Japan	10.–15.11.2024
DKV Tagung	Dresden, Germany	20.–22.11.2024
IRES International Renewable Energy Storage and Systems Conference		tba

December

MRS Fall Meeting & Exhibit	Boston, USA	01.–06.12.2024
Hydrogen Dialogue	Nuremberg, Germany	04.–05.12.2024

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

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