Fraunhofer ISE

Fraunhofer Institute for Solar Energy Systems ISE

Research for the Energy Transition

Annual Report 2024/25

The cover photo shows a detailed view of the first medium-voltage string inverter for large-scale PV power plants in the world (rear view). The string inverter, which we developed at Fraunhofer ISE, features a significantly higher output voltage than previous inverters. The higher voltage allows lower currents to be used, such that the diameter of electric cables can be reduced and valuable resources can be saved at the same time.

As the planned expansion of photovoltaics demands new infrastructure such as newly laid cables and new transformers, enormous amounts of raw materials such as copper and aluminum can be saved by using the medium-voltage string inverter.

Foreword

We are living in turbulent times. Every day, we hear news of wars, economic crises, and far-reaching political changes. As a result, climate change and the need to reduce greenhouse gas emissions are often relegated to the background in public debate. However, reaching climate-political targets as quickly as possible still continues to be urgently necessary, to prevent drastic changes in living conditions on our earth. For us at Fraunhofer ISE, this means contributing even more than previously to advancing a safe and stable energy supply based on renewable energy sources and supporting our economy in the development of the technologies that are needed to do this. Our orientation toward applied research and close relations to industry are strengths in this process.

In general, energy research in Germany had to adjust to a substantial reduction in funding last year, which impacted research institutions and the industry. As one of the leading institutes in energy research, we were greatly affected by these reductions. Despite decreasing public funding, we will continue to invest all our efforts in developing answers to open questions concerning the transformation of the energy system. In this context, it was even more satisfying that we were able to open two new research centers in the past year. At the beginning of the year, we celebrated the opening of the technology evaluation center, Module-TEC. Here, we can produce and evaluate PV modules in small series for our industrial partners. And in October, we officially opened the new Center for Electrical Energy Storage with a prominently attended ceremony. In the modern laboratories there, we research the sustainability, safety, and performance of battery storage units.

We find it very encouraging that photovoltaics is being used in an increasingly wide range of applications, whether as agrivoltaic systems in orchards or market gardens, as floating modules on water bodies, or for the restoration of moors. The technologies of "Integrated Photovoltaics" exploit an enormous additional potential of surface area for PV installation. As part of the revision of the German Building Energy Act, heat pumps were at the focus of media attention last year. The political discussions about heat pumps created uncertainty for consumers. With our research work, we intend to support industry and trade in regaining lost confidence by presenting hard facts. At the same time, widely based research, particularly on natural refrigerants and digital solutions, contribute to the capacity of the German industry for innovation.

In summer, we proudly celebrated the 10th anniversary of our "Energy Charts". An action that began in 2014 as a collection of presentation slides, it has since become a widely used website on energy data in Germany, which is accessed around 100 million times per year.

Again, we were particularly pleased about the numerous prizes and awards that researchers from the Institute have received for their work. This success would not have been possible without the ongoing enthusiasm and achievements of our staff, to whom we owe deep gratitude. We would like to mention by name Dr. Thomas Kroyer, Dr. Oliver Höhn, and Andreas Wessels, who were awarded the Joseph von Fraunhofer Prize for 2024 for the development of the MorphoColor® coating technology.

In October 2024, Dr. Elias Frei became the new Head of Hydrogen Technologies. Dr. Frei worked previously at BASF and we are very pleased that we were able to attract him to our institute. Since December 2024, Dr. Jasna Jankovic has been a guest research scientist at our institute. The professor from the University of Connecticut was awarded the Fraunhofer-Bessel research prize by the Alexander von Humboldt Foundation and will conduct research at Fraunhofer ISE on ex situ characterization methods for innovative fuel cells and electrolyzer materials – an honor and enrichment for our institute.

We extend our sincere gratitude to our Board of Trustees, industrial partners, scholarship donors, and funding agents 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. Dr. Hans-Martin Henning

Prof. Dr. Andreas Bett

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Organizational Structure

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 ISE 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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Profile

Goal

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 that 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. The 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 develop jointly with them. This is in accordance with the Fraunhofer principle of applied research and, at the same time, makes an important contribution to securing the economic future and competitiveness of Germany and Europe. The success of applied research demands transfer of our knowledge to politics and into society. Thus, an integral part of our R&D work involves exchange with relevant stakeholders, whom we address in eight market-oriented business areas (pages 22 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 transformation, our organizational structure is designed to promote interdisciplinary and cross-linked research.

Among other aspects, the success of our research is demonstrated by the total of 19 spin-off enterprises, which originated in the ISE over the years and which market newly developed promising technologies.

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 of our competence in research and development. Our infrastructure of the highest technical standard encompasses eight R&D Centers and three production-relevant Technology Evaluation Centers (pages 42 ff.). Furthermore, the institute offers testing and certification services in its test and calibration laboratories, which 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 – as required by the individual commissions, demands, and levels of technical 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 showing the sun deck of the canteen.

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 guests got together for the Board meeting in July 2024 in the Solar Info Center in Freiburg.

Networking within the Fraunhofer-Gesellschaft

Fraunhofer ISE contributes its wide spectrum of competence to various associations and alliances within the Fraunhofer-Gesellschaft. This approach benefits work on systemic questions and supports knowledge transfer.

Groups and Strategic Research Fields

The Fraunhofer Institutes work together within competence-oriented groups. Fraunhofer ISE is a member, together with three other institutes, of the Fraunhofer Group for Energy Technology and Climate Protection. 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 prominently represented in the role of speaker for two of the seven 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 Geotechnologies IEG are the speakers representing 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.

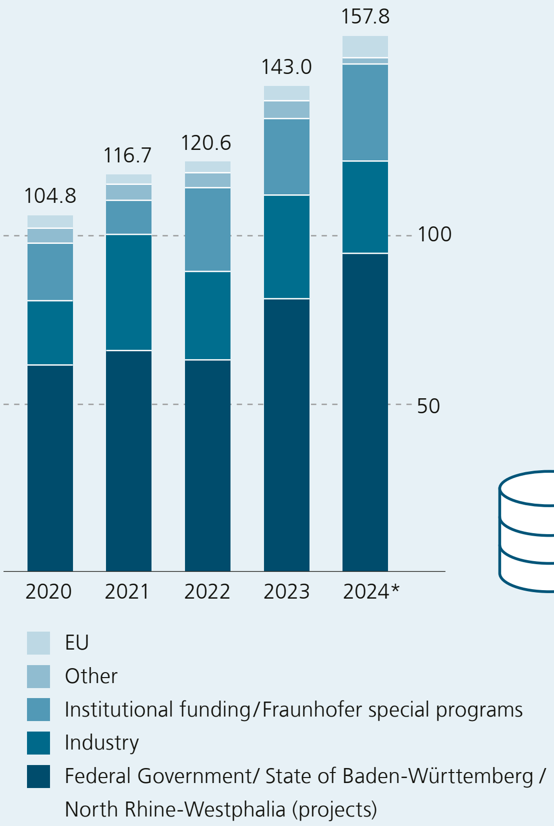
Fraunhofer ISE is one of 20 members of the Fraunhofer Energy Alliance and has been responsible for its management since its establishment in 2003. The Fraunhofer Energy Alliance organizes joint market access for its member institutes and responds to the needs of the energy-economic lead market. The Institute Director, Prof. Andreas Bett, and Prof. Christian Doetsch, Director of the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, have represented the goals of the Alliance to the outside world as its speakers since July 2024. They are the successors of Prof. Hans-Martin Henning, who acted as speaker from 2016 to 2024.

Further networking within the Fraunhofer-Gesellschaft includes memberships in the Alliances Building Innovation, Batteries, SysWasser, and Aviation & Space, as well as in the Fraunhofer Cluster of Excellence on Integrated Energy Systems (CINES) and the Fraunhofer Networks for Sustainability and Hydrogen.

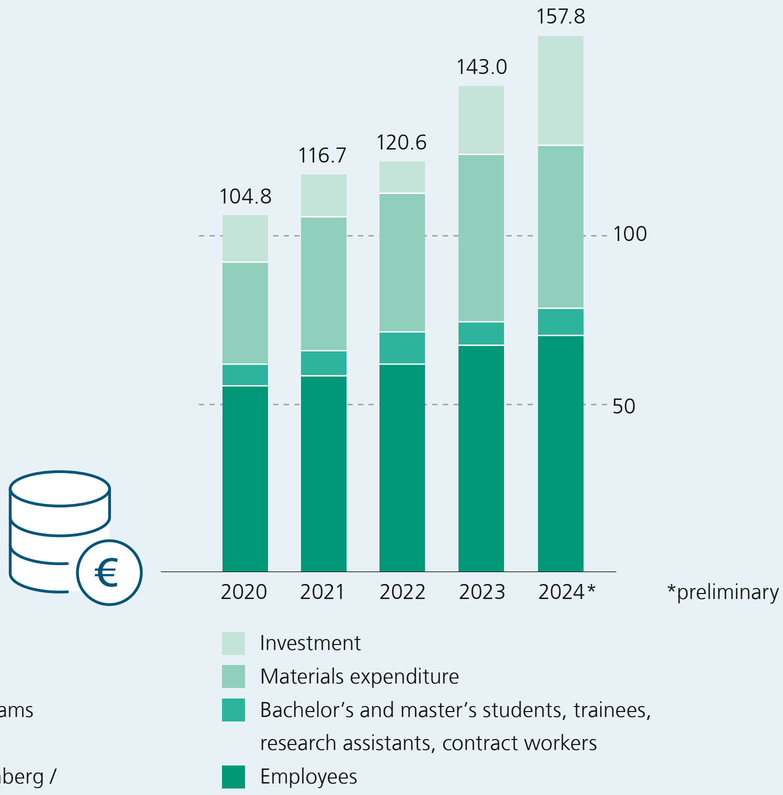
The Fraunhofer Energy Alliance presented its activities at a joint stand on Smart Energy from 20^{th} to 22^{nd} February 2024 at the E-World trade fair in Essen.

The Institute in Figures

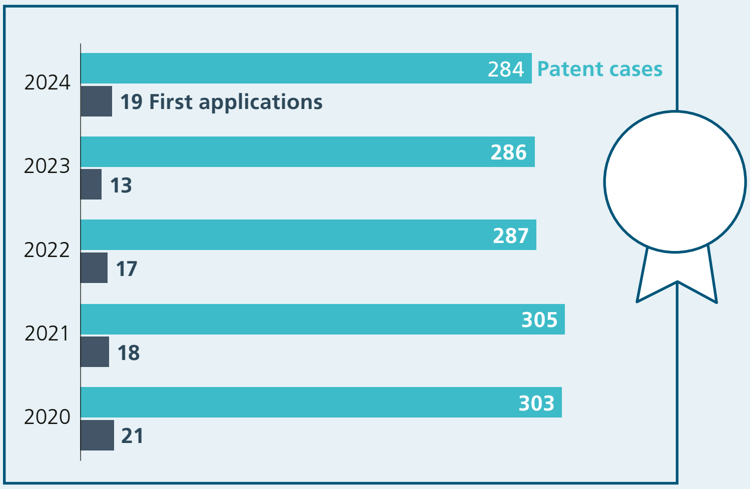
Income in million euros



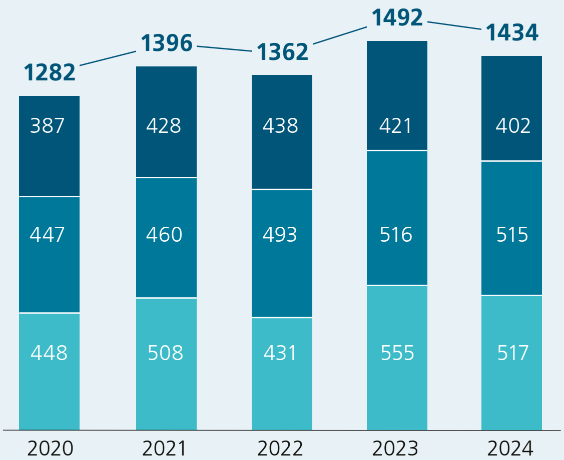
Expenditure in million euros

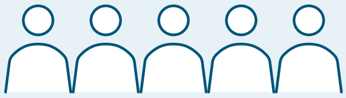


Patents

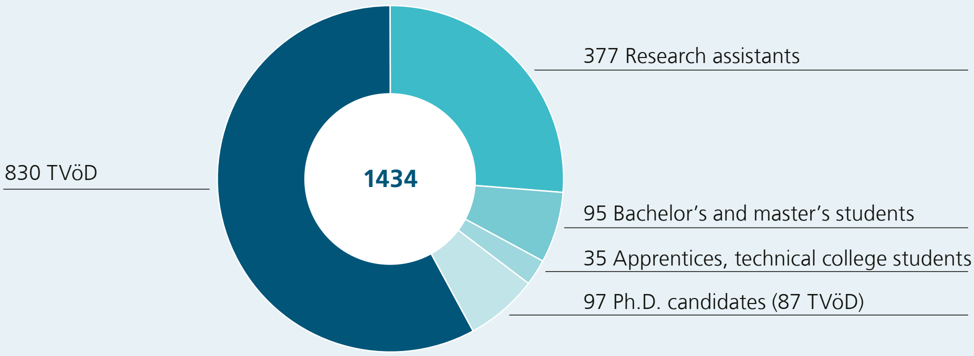


Personnel

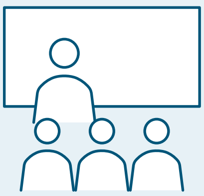


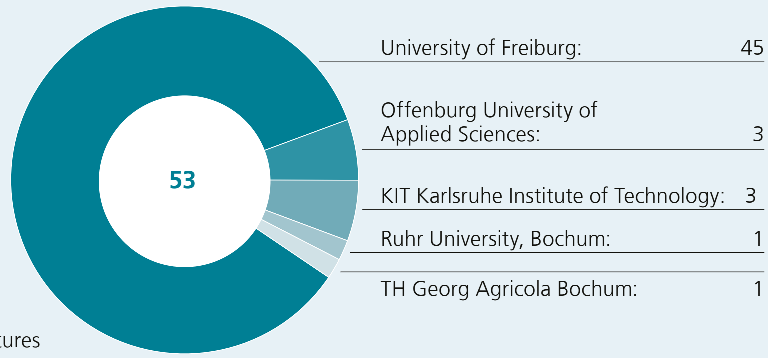


Personnel in 2024



Lecture Courses and Seminars



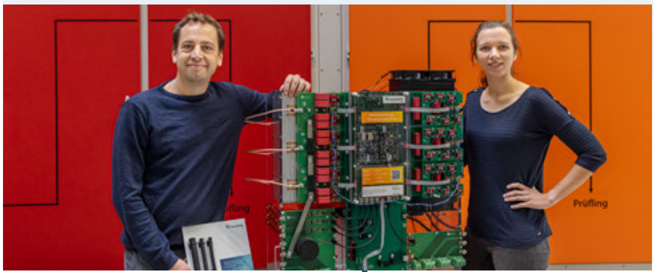


37 scientists of Fraunhofer ISE give regular lectures at universities, in addition to their research work.

Our Highlights in 2024

Visit from the German Chancellor, Olaf Scholz
On 27th February, Olaf Scholz visited Fraunhofer ISE. He learned about new technologies for energy-efficient buildings and intelligent charging infrastructure.

Zukunftspreis for Medium-Voltage String Inverter
Fraunhofer ISE gained 2nd place in the Zukunftspreis (Future Prize) of the Ewald Marquardt Private Foundation. We received the award for the development of the first medium-voltage string inverter for photovoltaics in the world. In the long term, we expect the subject of medium voltage to make the energy system more resource-efficient (p. 20).



Opening of Module-TEC
In February, Fraunhofer ISE opened the newly designed Module-TEC technology evaluation center, which occupies a floor area of more than 1 000 square meters. Prototypes up to small series of PV modules are manufactured and tested in the development and manufacturing environment (p. 40).

Joseph von Fraunhofer Prize
Dr. Thomas Kroyer, Dr. Oliver Höhn, and Andreas Wessels were honored with the Joseph von Fraunhofer Prize. The researchers received the prize for the development of the MorphoColor® coating technology.
ise.link/fraunhofer-prize

Reducing CO_2 Emissions from Industrial Plants with Propane Heat Pumps
We cooperated with partners to develop a heat pump with a propane cooling circuit for the industry. The application in a cleaning machine led to appreciable savings in electricity consumption and CO_2 emissions and provides a good example of how transformation of the industry can be promoted.
ise.link/heat-pump-industry

Hans-Martin Henning in the Advisory Board of the 8th German Energy Research Program

Prof. Hans-Martin Henning was appointed by the German Federal Minister for Economic Affairs and Climate Action, Robert Habeck, to the Advisory Board of the 8th Energy Research Program of the federal ministry (BMWK).

Energy-Charts Celebrates its 10th Anniversary

Facts instead of fake news: Ten years ago, we went online with the Energy-Charts data platform, to provide a factual basis for discussions about the energy transformation. Today, the website provides interactive data on German electricity generation, emissions, and prices as well as electricity generation and stock exchange data for 42 European countries. www.energy-charts.info

July

Center for Electrical Energy Storage Officially Opened

We have been conducting research along the whole battery value chain for many years. With our new Center for Electrical Energy Storage, extremely modern laboratories are now available for cutting-edge research. The research focuses on improving the sustainability, safety, and performance of battery storage units (p. 41).

November

Report on Climate-Neutral Energy System Published

The new report demonstrates technological routes that could be taken to transform the German energy system to climate neutrality by 2045 at the level of the German federal states.

December

Successfully Completed Ph.D. Studies

15 young scientists successfully completed their Ph.D. studies while working at Fraunhofer ISE in 2024 (p. 15). We aim to support Ph.D. students even further and make Ph.D. studies more attractive.

Partner for Industry

Which solutions and technologies are needed to realize the energy transformation? How can innovation, sustainability, efficiency, and competitiveness of the German and European economies be increased? As an experienced sparring partner for industrial enterprises, Fraunhofer ISE supports its partners in bringing innovations for all aspects of renewable energy technologies successfully to the market and to advance climate-neutral industrial processes.

We live out the Fraunhofer model of applied research and offer a comprehensive program of R&D work in eight market-oriented business areas. Professional cooperation with industrial partners is paramount for us. We take the time to exchange information in meetings or webinars, invite our partners to workshops at the Institute or visit our industrial clients at their premises.

In the photovoltaic sector, we support companies that aim to build up their production capacity, for example, by the selection of suitable technology, and help with process development, product design, factory layout, and factory establishment. Beyond that, we accompany industrial clients during transformation, e. g., by offering solutions for climate-friendly operation of industrial plants.

Living Labs – Testing Innovations in Practice

Together with Vattenfall Wärme Berlin AG, EnBW, and several municipal utilities, we are testing the connection of large-scale heat pumps to district heating networks at five locations. The results of the Living Lab "Großwärmepumpen in Fernwärmenetzen" (large heat pumps in district heating networks) support the design process for heat pump systems intended for application in municipal heating networks. The German Federal Ministry for Economic Affairs and Climate Action (BMWK) is funding the joint project until 2026.

Research	Materials, new components, proof-of-principle, simulation and modelling, methods
Development	Equipment, process technologies, transfer to production scale, proof-of-concept
Market introduction	System design, monitoring, demonstration, testing and certification, quality assurance

We carry out research and development work for industry and public bodies. Beyond that, we also support successful market introduction.

At present, we are researching promising technologies for the future in more than 1200 projects for industry and public bodies. Beyond that, we are represented in numerous boards for politics, industry, and associations and participate in the regulation and standardization of new procedures, to increase planning security and quality assurance.

Cooperation

Scientific excellence depends on discourse between experts. Fraunhofer ISE is part of an active research network at both the national and the international levels.

Cooperation with Universities

Fraunhofer ISE places great value on educating future scientists. Currently, 37 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 Faculty of Physics and 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 with 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 Faculty of Environment and Natural Resources and the Faculty of Chemistry.

Among the courses that 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. course on "Solar Energy Engineering".

Memoranda of Understanding

In addition, the Fraunhofer ISE maintained 7 Memoranda of Understanding with enterprises, organizations, and research institutes around the world in 2024. It is well connected at the national and the international levels within research and professional associations.

Research for the future: Fraunhofer ISE is also engaged in educating young scientists.

Prizes and Awards

Fraunhofer ISE

- BestChance Award 2024, Fraunhofer-Gesellschaft
- German Sustainability Award, nomination in the Research and Science Category
- ESG Transparency Award, EUPD Research

Cornelius Armbruster, Florian Bierwirth, Samuel Hohler
Pfiffikus Gründerideenpreis (prize for spin-off idea) 2024, EDENenergy, University of Freiburg

Stephan Armbruster
Innovation Prize, B.Sc. Thesis "Ex-situ Visualization and Analysis of the Two-Phase Fluid Dynamics in PEM Water Electrolyzer Cells", Deutscher Wasserstoff-Verband (DWV)

Oussama Er-Raji
Student Award "Tailoring Perovskite Crystallization and Interfacial Passivation in Efficient Fully-Textured Perovskite Silicon Tandem Solar Cells", EU PVSEC 2024

Michael Geiss, David Derix, Andreas Hensel, Jürgen Thoma, Dirk Kranzer
Future Prize, 2nd place, Development of Medium-Voltage String Inverter, Ewald Marquardt Private Foundation

Dr. Sebastian Gölz
TOMMI Award, "Little Impacts", Büro für Kindermedien FEIBEL.DE

Dr. Oliver Höhn, Dr. Thomas Kroyer, Andreas Wessels
Josef von Fraunhofer Prize 2024, MorphoColor® Coating Technology, Fraunhofer-Gesellschaft

Dr. Robin Lang
Best Oral Presentation Award, 35. International Photovoltaic Science and Engineering Conference, Japan

Dr. Alexander Morgenstern, Norbert Pfanner
IEA-SHC 2024 Solar Award, Shortlist, SolCoolDry project

Anna Rothenhäusler
Gerda Ruf Award, M.Sc. Thesis "Control of Battery Systems with Reinforcement Learning", Fritz Hüttinger Stiftung

Dr. Torsten Rößler
SiliconPV Award 2024, "Industrial Scale Perovskite Silicon Tandem Module with 24.4 % Module Efficiency"

Christian Schmiga
Poster Award, "Optimizing Mechanical and Electrical Properties of Ni/Cu/Ag-Plated Contacts on i-TOPCon Solar Cells", EU PVSEC 2024

Dr. Patrick Schygulla
Dr. Fritz Ruf Award, Ph.D. Thesis, "III-V Semiconductor Subcell Absorbers in Silicon-Based Triple-Junction Solar Cells", Fritz Hüttinger Stiftung

Jeannette Wapler, Huang Mu, Sebastian Helmling
EHPA DecarBuilding Award, HAPPENING project, European Heat Pump Association

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

Anahí Romero Arellano
"Development and Optimization of a Slot-Die Coating Process to Produce Anode Catalyst Layers for PEM Water Electrolysis"

Vera Büttner
"Investigation of Ammonia Adsorption under PtX Synthesis Conditions"

Alain Cerny
"Prelithiated Silicon as Anode Material for All-Solid-State-Batteries"

Anna Damm
"Comparison of the Hydrogenization Properties for Passivating Contacts with N-Doped and P-Doped Polycrystalline Silicon"

Tom Hoger
"Effects of Structural Changes in Metal Meshes on the Flow of Shear-Thinning Fluids Using CFD Simulation"

Jenny Norberg
"Film-Based Nano-Imprint Lithography for Photonic Structures in Photovoltaics"

Doctoral Theses in 2024

Saed Al-Hajjawi
"Inline and Offline Characterization of Epitaxial Wafers for Industrial Application"
University of Freiburg

Rodrigo Delgado Andrés
"Organic Solar Cells in Photo-Electrochemical Storage Devices"
University of Freiburg

Christian Diestel
"Photosupercapacitors – Development & Advanced Characterisation"
University of Freiburg

Malte Gierse
"Development of a Power to Liquids Process for the Production of Dimethyl Ether by Dehydration of Methanol in a Reactive Distillation Column"
Karlsruhe Institute of Technology

Sina Herceg
"Assessment of the Ecological Lifetime of Photovoltaic Systems Considering Aging Effects, End-of-Life and Early Replacement"
Technical University of Darmstadt

Leonie Jakob
"Through-mask Electrochemical Machining for Conductor Track Manufacturing: Fundamental Insights and Practical Implications"
University of Freiburg

Özde Şeyma Kabaklı
"Optimization of the Perovskite Top Solar Cell in Monolithic 2-Terminal Perovskite Silicon Tandem Solar Cells"
University of Freiburg

Stephan Maus
"Investigation and Modelling of Charge-Carrier Recombination by Oxygen Precipitate Formation in Cz-Si during High-Temperature Processes in Photovoltaic Applications"
University of Freiburg

David Müller
"Fabrication, Optimization and Characterization of ITO-Free Organic Solar Cells and Modules for Indoor Applications"
University of Freiburg

Tabea Obergfell
"Evaluation of the Long-Term Functionality of Paraffin-Based Phase Change Materials in Building Applications"
Karlsruhe Institute of Technology

Jan Paschen
"New Concepts for Solar Cell Connection with Laser Soldering of Thin Aluminum Films"
University of Freiburg

Sebastian Praß
"CO and H_2S in H_2: Contamination, Recovery and Mitigation Strategies in PEMFCs with Ultra-Low Pt Loaded Anode Electrodes"
University of Stuttgart

Matti Sprengeler
"Prescriptive Urban Analytics – The Case of Electric Vehicle Charging Infrastructure"
University of Freiburg

Raphael Vollmer
"Renovation Paths to Integrate Heat Pump Systems into Existing Medium-Density Buildings"
University of Freiburg

Andreas Wessels
"Spectrally Selective Photonic Structures for Colored Design of Integrated Photovoltaic Systems"
University of Freiburg

Strategy and Business Areas

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Our aspiration: excellent research for our industrial partners to implement a sustainable energy supply."

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

Reliable Guidance and Confidence in the Transformation of the Energy System

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

Implementation of the German energy transformation has gained significant momentum in recent years. Does this affect Fraunhofer ISE positively?
Henning: It is correct that new installations have increased enormously, particularly in photovoltaics. However, the companies that are responsible for the expansion are generally not the direct clients of Fraunhofer ISE. The manufacturing industry, which cooperates with us on research and development, is having more difficulties at present in Germany. This applies to PV manufacturers but also to other sectors, for example batteries, where the hopes of European enterprises have been greatly dampened. The heating sector is also struggling because the market uptake of heat pumps does not take place as planned. Of course, it is a positive sign that we already have so much renewable energy in the system, but we are still very much at the beginning in the end-use sectors, meaning buildings, transport, and industry. The transformation that lies ahead of us is a major task and it requires significant investments. It is therefore important that society and politics trust in the need for investments in structural change to achieve climate goals. But also that these can help secure our economic future.

The political hesitance was also manifested by reduced German research funding in the energy sector by 30 %. What were and are the effects on the ISE?
Bett: Particularly reductions in financial support from the climate and transformation fund had a strong effect, not only on Fraunhofer ISE but also on the whole sector. As a result, we and our clients could not carry out as many R&D projects as originally intended. In addition, due to the federal elections at the beginning of 2025, there will be delays until the federal budget is approved and the research funding strategy is defined. Thus, approval of further planned research projects will not be possible for some time. Consequently, at present, we are experiencing financially difficult times that will certainly continue, such that ISE must consolidate and focus more strongly. We are critically examining which market segments are no longer large enough for us and which topics will be discontinued. However, we must also make adjustments concerning R&D topics that we deem as highly relevant for the success of the energy transformation. We will be unable to extend increasing numbers of contracts that were planned for our employees.

Many German and European manufacturers are also in a difficult situation and invest less in R&D. What is the reason for this in the current phase of the transformation?
Henning: Difficult conditions for the economy in general are playing a major role: the price of energy, bureaucracy, the lack of a skilled workforce in various areas. The cost for expanding the grid as required is a major contributor to the high electricity costs. Other solutions should be found for these infrastructure costs, as is currently happening in the extension of hydrogen infrastructure. Particularly in photovoltaics and battery technology, international competition poses many difficulties for German manufacturers. However, another problem is political uncertainty: Will the CO_2 reduction goals and the planned implementation rates be retained? What we need here, above all, is reliability, so that businesses become willing to invest in the future.

Bett: As part of the Green New Deal, the European Union is making it possible to focus on economic resilience. It is a fact that many components can be produced less expensively in China and other Asian countries. We must find solutions to guarantee a certain technological sovereignty and independence in Europe. The Green Tech technologies also affect our future economic opportunities. Our institute sees enormous potential for various technologies and we want to help the industry to implement industrial production in Europe by developing improved processes at lower costs.

There is hardly any PV manufacturing in Germany anymore. Why did the ISE officially open the new Module-TEC in 2024, despite this situation?
Bett: Integrated photovoltaics, which we have been advancing at the Institute for many years, shows us that not only mass production of inexpensive silicon standard modules is important but that there is also a need for many different types of modules for specific applications in the double-digit gigawatt range.

This is a market that European manufacturers can supply very well. Beyond that, we are working in Module-TEC on production processes for new technologies such as tandem solar cells, which are already entering the market.

How can the newly opened Center for Electrical Energy Storage increase the competitiveness of German battery production?
Henning: In particular, expansion of the stationary storage infrastructure is extremely important for the transformation of the energy system. At the same time, there is still a great opportunity for research and development of batteries – from optimization at the material and cell levels, through the improvement of production processes, up to better control systems for mobile and stationary applications. With the Center for Electrical Energy Storage, we have created a good basis to contribute here. We also reached important milestones in battery technology in the recent past, for example concerning anode technology or the utilization of more sustainable battery materials such as sodium or zinc. As a result, we are very confident that we can support German and European companies in bringing competitive products on the market.

Fraunhofer ISE has initiated "Medium Voltage" as a key topic. Why is that a strategic subject for the institute?
Bett: In future, our energy system will be based increasingly on electricity. The required expansion of the grid infrastructure needs large amounts of electric power and components and thus very large amounts of raw materials, such as copper and aluminum. A holistic awareness of sustainability concerning the energy transformation is important to us; among other aspects, this means that we take account of the efficient use of resources. For this reason, we see great opportunities for the application of medium voltage, e.g. for the components of PV power plants and connection technology between modules, up to the grid connection point. The higher voltage means that resistance losses are reduced and thus less material is required. This saves costs and resources. Thus, we are cooperating with industrial partners, to achieve a commercial breakthrough for medium-voltage components and cables.

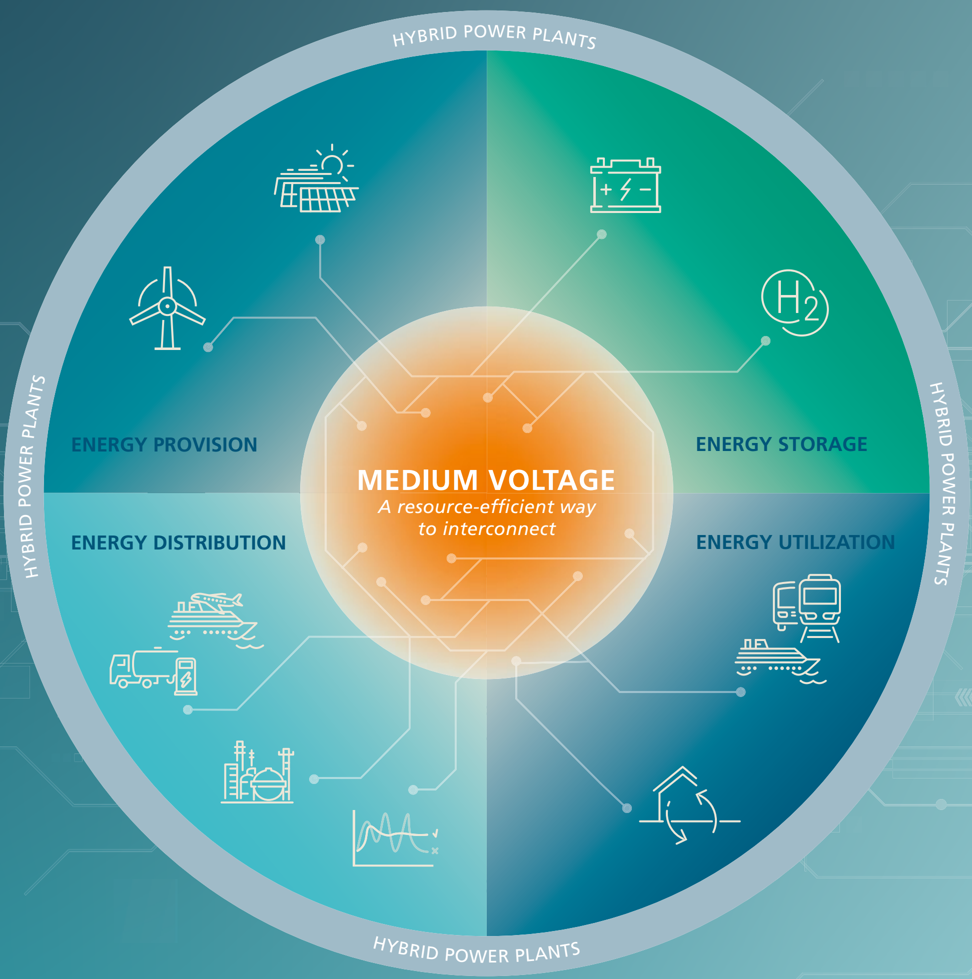
Hydrogen will play a major role as a storage medium and for the decarbonization of industrial processes. Politics has started to set the scene for hydrogen infrastructure in Germany. What is the position of ISE?
Henning: That is true. In future, large amounts of hydrogen will be needed and imported for various sectors. At Fraunhofer ISE, we are researching synthesis routes to convert hydrogen into higher-value molecules, to make cost-effective and efficient transport feasible. On the other hand, we are developing technologies further to produce green hydrogen cost-effectively and to use it in fuel cells. In specific terms next year we are planning to commission new facilities to develop production technology for membrane-electrode assemblies in fuel cells.

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

Thereby we aim to significantly reduce the production costs for the converters – in fuel cells and in electrolyzers – by producing them industrially on a large scale. In future, it will be the equipment cost that determines the price for green hydrogen. We aim to make our contribution here.

Which other topics are relevant for you in 2025?
Henning: One important topic will continue to be heat pumps and our research on propane as a climate-friendly refrigerant. Here, it is now a matter of widespread introduction of this technology, for example to replace flat based heating units by heat pumps.

Bett: In 2025, we expect to start establishing a laboratory production line for perovskite-silicon tandem cells on industrial-size wafers, to promote even more the market introduction of this technology with its high efficiency. We are continually investing in the expansion of our infrastructure for central R&D questions, where we are convinced that our competence will be needed in many places to achieve the successful transformation of our energy system.



Medium Voltage – A Resource-Efficient Way to Interconnect

Large amounts of raw materials are needed to transform the energy system. For example, copper and aluminum are needed for the cables that connect renewable energy converters to the electricity grid. Fraunhofer ISE is demonstrating a promising approach to reduce the demand for raw materials in this sector: Generation, distribution, and utilization of renewable electricity could occur in future at the medium-voltage level rather than the low-voltage level, as in the past. We see enormous potential for saving resources by operating with higher system voltages, particularly with regard to large-scale photovoltaic power plants. We are thus already planning pilot power plants and are cooperating with the industry to achieve broad market introduction. To underline the importance of this topic, we have identified “Medium Voltage” as a research focus for the immediate future.

By 2050, the planned global expansion of more than 70 terawatt of installed photovoltaic power alone will already be accompanied by a strong demand for raw materials. According to the report by the International Energy Agency entitled “Global Critical Minerals Outlook 2024”, the demand for copper will exceed the predicted supply from 2025 onward. This trend can be partly compensated for by raising the system voltage, because the associated reduction in current can result in significant savings in raw materials: Increasing the output voltage from 800 V_{AC} to 1500 V_{AC} results in a reduction of the cable cross-section by approximately 75 % for the same transmitted power. At the same time, cables with a smaller circumference are easier to install and connect, such that installation costs also decrease.

Overall, electricity from renewable energy sources is becoming increasingly affordable: Thanks to technological progress and scaling effects, PV module costs have fallen by 90 % since 2010. Now, installation and balance-of-system components offer the greatest cost-saving potential. By taking the step from low to medium voltage, the power of sub-systems can be greatly increased; at a voltage of 1500 V, already 10 to 12 MVA can be transmitted through a transformer, instead of the values of 3 to 5 MVA that are common today. For the same power plant size, fewer transformers and less switching equipment are needed, so that the specific construction and installation costs decrease.

The Technological Course has been Set

The step towards the introduction of medium voltage only became feasible due to the development of highly blocking silicon carbide (SiC) semiconductor devices with high switching rates. At present, SiC devices for up to 3.3 kV are commercially available. Based on these components, Fraunhofer ISE developed the first medium-voltage PV string inverter in the world within the "MS-LeiKra" project, and successfully took it into grid-connected operation. The two-stage inverter has an output power of 1500 V_{AC} for a power of 250 kVA. We used this to demonstrate that the technological scene is set for the transition to medium voltage. As the industry is extremely interested in this technology, we at Fraunhofer ISE are convinced about the relevance of the topic. Now, it is a matter of determining who will be the first actors in this promising market.

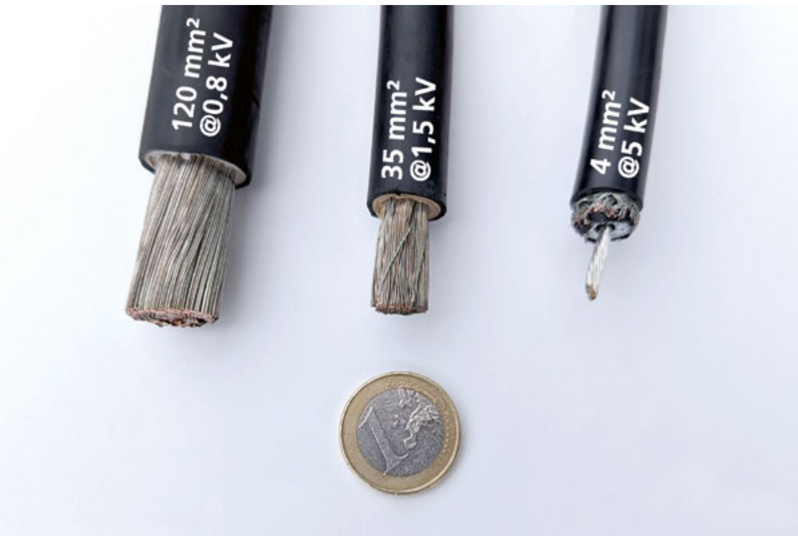
Overcoming Obstacles Together

As part of a workshop devoted to the topic of medium-voltage PV, we have already established a European consortium. Representatives of all the trades and professions that are involved in a large-scale PV power plant use this platform to exchange the information needed to prepare the technological and regulatory prerequisites for the leap into medium voltage. With this consortium, which is open to further interested participants, we will overcome the existing hurdles together. Our goal is to create a network of European manufacturers involved in this important technological step and to support them with cutting-edge research. Thus, European manufacturers could take on a leading role here and control the market not only for PV modules but also for the complete PV systems technology. In order to demonstrate feasibility also in practice, the consortium is aiming to build pilot power plants based on the medium-voltage PV string inverter developed at Fraunhofer ISE.

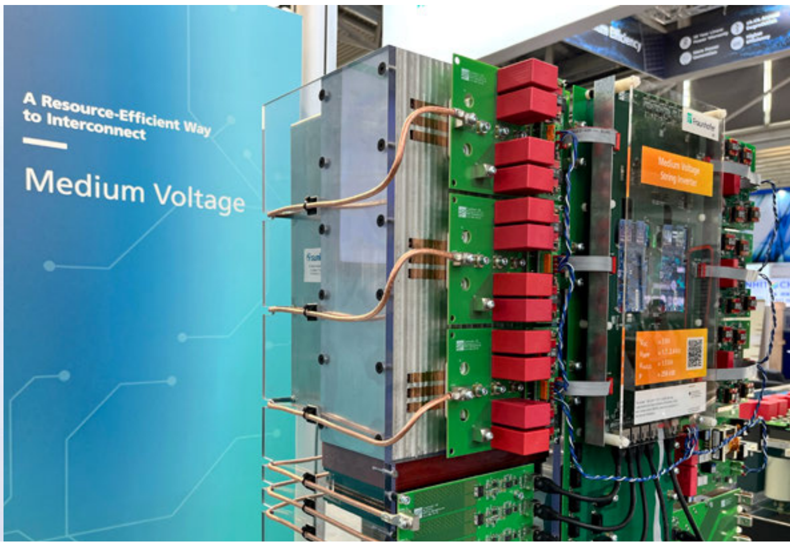
Intensive work on this topic is also carried out with regard to standardization. Already, the first draft standards have been prepared for some components up to 3 kV and information is being exchanged between the various relevant technical committees. We are also engaged in proposing an international standard for the medium-voltage range to integrate renewable energy applications.

We regard the operation of large-scale PV power plants with medium voltage as only the first step – charging infrastructure, industrial grids, large heat pumps, battery storage units, electrolyzers, or wind energy systems also present interesting application areas for the low medium-voltage level. Higher system voltages not only make significant savings in materials, cost, and surface area feasible, but they also enable completely new system architectures for regenerative hybrid power plants, where the individual components are connected to each other via medium voltage. Thanks to many years of experience and interdisciplinary competence, we at Fraunhofer ISE offer clients all services from a single source, ranging from research and development, through the characterization and testing of components and systems, up to the conception of hybrid power stations.

Comparison of minimum cable cross-sections for 250 kVA at different voltage levels.



The first medium-voltage string inverter in the world for future large-scale PV power plants.



Photovoltaics: Materials, Cells and Modules

Market Position

High conversion efficiencies and the resulting low-level costs of photovoltaic electricity can only be achieved with optimal and cost-efficient materials. For silicon, organic, III-V, and perovskite semiconductors, we at Fraunhofer ISE achieve very good electronic properties by in-depth analyses and optimized processes. Building on this basis, 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 production, 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.

172 Total staff

57 Journal articles and contributions to books

89 Lectures and conference papers

4 Newly submitted patent applications

Leadership

Prof. Stefan Glunz, +49 761 4588-5191

Topics

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

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

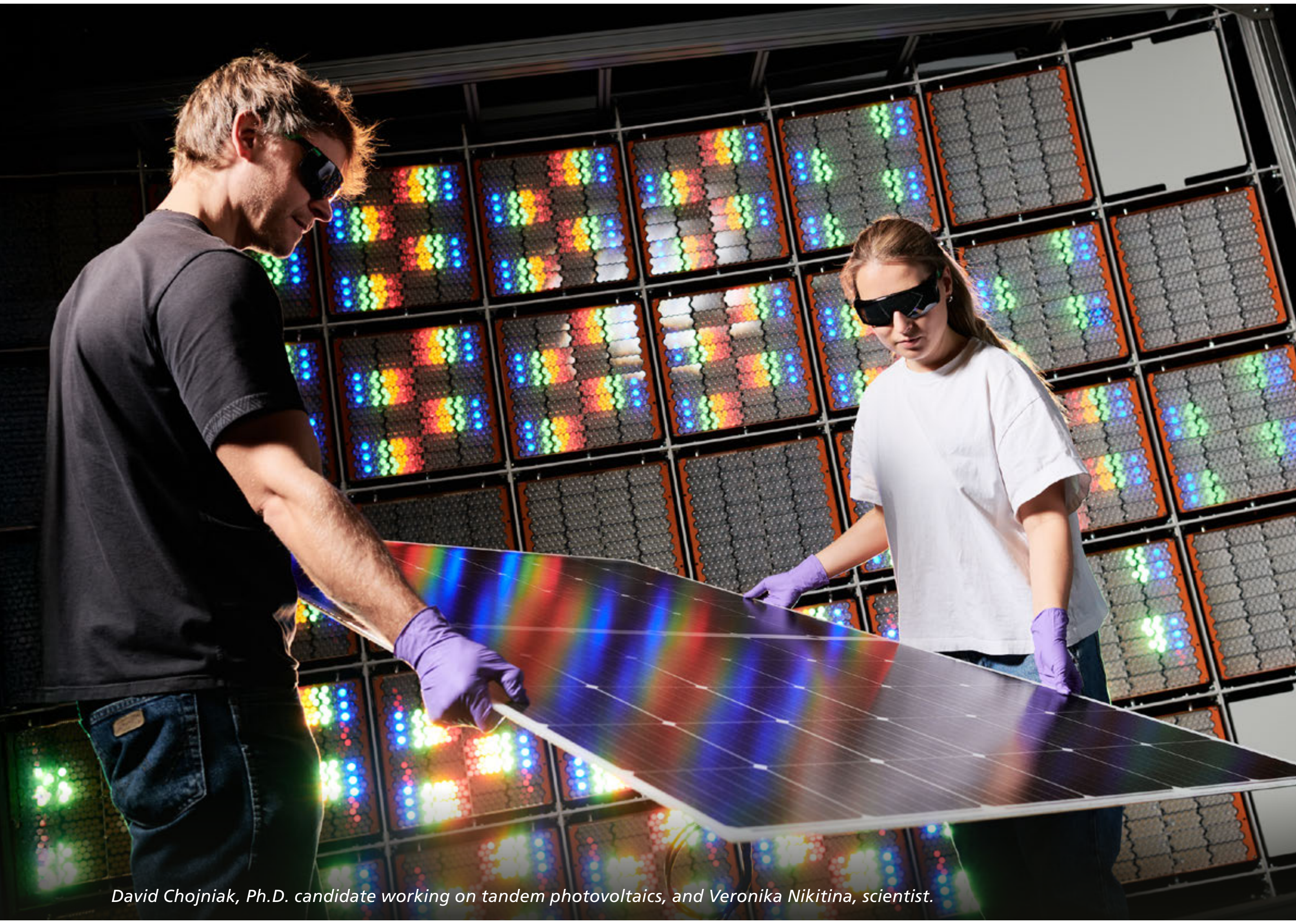
Silicon-Based Tandem Solar Cells and Modules
Dr. Martin Hermle, +49 761 4588-5265

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

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

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

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



David Chojniak, Ph.D. candidate working on tandem photovoltaics, and Veronika Nikitina, scientist.

"We are developing innovative concepts and materials for more efficient, stable, and cost-effective solar cells and modules."

More information on projects, publications, and topics of this business area:

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. At present, numerous production technologies exist, including wet chemical processes, epitaxial procedures to produce materials, or laser and printing processes for solar cell manufacture. In addition, coating processes and connection and lamination technologies are applied in module production. The applied processing and characterization equipment must guarantee high performance, reproducibility, and output 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 corresponding materials and equipment required. 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.

214 Total staff

14 Journal articles and contributions to books

49 Lectures and conference papers

5 Newly submitted patent applications

Leadership

Dr. Ralf Preu, +49 761 4588-5260

Topics

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

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

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

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

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

Interconnection and Encapsulation Technologies
Dr. Holger Neuhaus, +49 761 4588-2579

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

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

René Haberstroh, engineer.

"Our technologies make PV modules more sustainable by conserving material resources and increasing efficiency and productivity."

More information on projects, publications, and topics of this business area:

Solar Power Plants and Integrated Photovoltaics

Market Position

We conduct research so that innovative, high-quality, and cost-effective solar systems can be established on all suitable surface areas. For 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 power prediction is becoming increasingly important. We are thus developing prediction models for reliable forecasts of solar electricity generation.

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. Furthermore, our team characterizes the performance of new module technologies and tests their reliability in the laboratory and in the field. Our research also addresses solar-thermal power stations and their combination with photovoltaics and power-to-X technologies.

150 Total staff

28 Journal articles and contributions to books

48 Lectures and conference papers

Leadership

Dr. Anna Heimsath, +49 761 4588-5944

Topics

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

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

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

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

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

Maddalena Bruno, Ph.D. candidate in the Photovoltaic Power Plants Department.

"Efficient use of surface areas: our integrated PV technologies bring more solar energy into urban and rural areas."

More information on projects, publications, and topics of this business area:

Power Electronics and Grids

Market Position

The integration of renewable energy into the energy system is increasing – as is the electrification of the energy supply in the electricity, heat, and mobility sectors. Along the route 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 converters 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 transformation with the available and exploitable raw material resources. Interoperability, digitalization, and modeling of energy systems is also becoming increasingly important. In a distributed electricity grid without conventional power plants, power converters 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".

Leadership

Christian Schöner, +49 761 4588-2078

Topics

Power Converters
Stefan Reichert, +49 761 4588-5476

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

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

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

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

86 Total staff

4 Journal articles and contributions to books

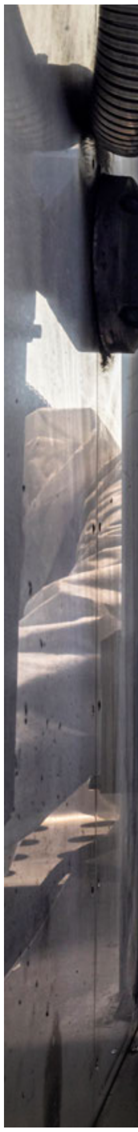
19 Lectures and conference papers

Henrike Köhler, Ph.D. candidate in the Power Electronics and Electricity Grids Department.

"Power electronics and digitalization of electricity grids are key technologies for a reliable power supply."

More information on projects, publications, and topics of this business area:

Electrical Energy Storage



Market Position

The energy transition and a sustainable transformation of the mobility sector can succeed only with the help of safe, sustainable, and high-performance battery storage units. The demand for corresponding battery technologies is thus increasing exponentially. Scaling effects and new technologies, which we are developing intensively, contribute to further rapid cost reduction. Digitalization and the application of Artificial Intelligence play a central role in the development, production, utilization phase, and end-of-life (EOL) areas.

The specifications that are defined as part of the battery passport – e.g. concerning transparency about the condition and remaining lifetime of batteries – encourage further development and acceptance of storage technologies. With our developments, we support our partners in complying with the corresponding regulations.

In our "Center for Electrical Energy Storage", we are working together with our partners on the next generation of lithium-ion batteries and promising alternatives such as zinc-ion or sodium-ion technologies. We take the entire value chain into account – from materials and cells through battery systems technology up to diverse storage applications. In our laboratory infrastructure, we offer extensive scientific tests at the cell and system levels, as well as modern characterization and production processes.

96 Total staff

18 Journal articles and contributions to books

18 Lectures and conference papers

2 Newly submitted patent applications

Leadership

Dr. Daniel Biro, +49 761 4588-5246

Topics

Battery Materials and Cells
Dr. Lea Eisele, +49 761 4588-2585

Battery Engineering
Dr. Nina Kevlishvili, +49 761 4588-2042

Production Technology for Batteries
Marc Kissling, +49 761 4588-2838

Battery Integration and Operational Management
Nils Reiners, +49 761 4588-5281

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

Digitalization in Battery Research and Production
Dr. Moritz Kroll, +49 761 4588-2554

Nikolaus Lang, Laboratory Manager, Battery Abuse Unit

We are improving electrical energy storage units and their integration at all levels, to support transformation of the energy and transport sectors."

More information on projects, publications, and topics of this business area:

Climate-Neutral Heat and Buildings

Market Position

The transition to renewable energy carriers is becoming increasingly urgent, not only to protect the climate but also to ensure supply and price security. In the building sector, the specific challenge is to provide technical and systemic solutions that address a wide range of actors. Possible solutions include technology for heat generation without fossil fuels, transformation concepts for the housing sector, industry and commerce, and heat supply, as well as 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 for an accelerated uptake of heat pumps with natural refrigerants to succeed in the building sector, we technologically support 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 heat networks and industrial applications. Furthermore, we work on integration of the equipment into each specific application.

221 Total staff

30 Journal articles and contributions to books

46 Lectures and conference papers

4 Newly submitted patent applications

Leadership

Sebastian Herkel, +49 761 4588-5117

Topics

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

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

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

Heat Pumps
Dr. Marek Miara, +49 761 4588-5529

Heat and Cold Storage
Dr. Sebastian Gamisch, +49 761 4588-5468

Ventilation, Air-Conditioning, Refrigeration
Dr. Lena Schnabel, +49 761 4588-5412

Water Treatment and Materials Separation
Dr. Joachim Koschikowski, +49 761 4588-5294

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

Timo Methler, Leader of Building Heat Pumps Team.

"We are supporting the industry in implementing the heat transition with intensive research on integrated processes and technologies."

More information on projects, publications, and topics of this business area:

Hydrogen Technologies

Market Position

Green hydrogen and its derivatives, such as methanol, ammonia and dimethyl ether (DME), can replace fossil fuels in many different applications: as a fuel, a reducing agent, and as basic chemicals in the steel, fertilizer, cement, or chemical industry. Green hydrogen technologies also offer great potential as fuels in the mobility sector and for power stations and for high-temperature applications.

With our expertise, we support industrial and research partners in the development of efficient technology along the entire value chain. Our core competence is in the development, production, and characterization of catalytically active components – which can be the reactor to produce hydrogen derivatives or the membrane electrode assembly in membrane electrolyzers or fuel cells. In addition, we carry out lifecycle and techno-economic analyses, in which we can identify and evaluate the sustainability and costs of solutions for the production of hydrogen and its derivatives, their efficient storage and customized global and local distribution.

152 Total staff

23 Journal articles and contributions to books

26 Lectures and conference papers

4 Newly submitted patent applications

Leadership

Dr. Elias Frei, +49 761 4588-5195

Topics

Fuel Cell
Ulf Groos, +49 761 4588-5202

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

Sustainable Synthesis Products
Dr. Achim Schaadt, +49 761 4588-5428
Robert Szolak, +49 761 4588-5319

Emma Verkama, scientist, and Thomas Cholewa, Ph.D. candidate working on power-to-X technologies.

"We are developing hydrogen technologies that enable the storage of and global trade with renewable energy."

More information on projects, publications, and topics of this business area:

System Integration

Market Position

System integration plays a central role in the targeted transformation of our energy supply to a net-zero energy system. Many components to provide emission-free energy are competitive today – but their integration into a complete, transsectoral energy system is still a great challenge, due to slow grid extension, hesitant digitalization, and the need to adapt regulations. The heat, electricity, and mobility sectors will need to interact increasingly in future. This applies to distributed energy systems, which contribute to more flexible consumption, generation, and storage, as well as to the extension of electricity grids and heat and gas networks.

Intelligent system integration must comply with many criteria, including supply security and affordability. It opens up great potential for making climate-neutral industrial production more flexible, for instance, when electric vehicles capable of feeding charge back into the grid act to shave generation peaks from a local PV system or to reduce expensive load peaks in the grid. Predictive operation management for the storage of renewably generated energy offers high utilization potential for the coupling of the electricity and heat sectors because inexpensive thermal storage can be used. The utilization of hydrogen via electrolysis also presents an important approach. We are cooperating with our industrial partners to research and develop corresponding holistic solutions for concrete energy transformation on site and test them together in living labs.

60 Total staff

19 Journal articles and contributions to books

36 Lectures and conference papers

Leadership

Prof. Christof Wittwer, +49 761 4588-5115

Topics

Energy System Analysis
Dr. Christoph Kost, +49 761 4588-5750

Integrated Energy Infrastructures: Electricity, District Heat, Gas
Prof. Christof Wittwer, +49 761 4588-5115

Energy Data and Monitoring
Nicolas Réhault, +49 761 4588-5352

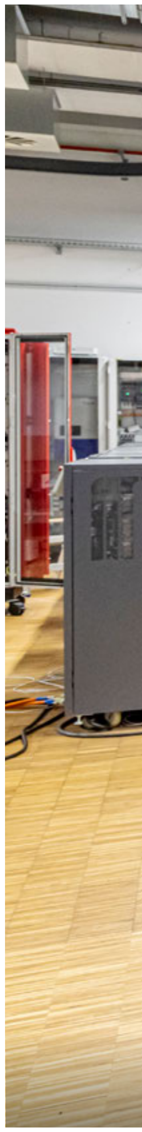
Flexibility Management of Energy Systems
Arne Surmann, +49 761 4588-2225

Energy Solutions for Industry
Dr. Thomas Fluri, +49 761 4588-5994

Climate-Neutral Cities, Urban Districts and On-Site Systems
Dr. Annette Steingrube, +49 761 4588-5062

Electric Mobility
Dr. Robert Kohrs, +49 761 4588-5708

Living Labs
Gerhard Stryi-Hipp, +49 761 4588-5686



Jan Körber, M.Sc. student.

Intelligent system integration is essential for an energy supply system based on renewable energy sources."

More information on projects, publications, and topics of this business area:

Research and Development – 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. In particular, small and medium-sized enterprises without their own R&D departments benefit from access to high-performance laboratory infrastructure and excellent research achievements by cooperating with Fraunhofer ISE.

In its seven accredited laboratories, the ISE offers diverse testing and certification procedures to commercial enterprises and scientific institutions. At present, Fraunhofer ISE 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. 42 ff.).

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

Research work in the Center for Electrical Energy Storage.

Laboratory Centers

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

Technological Evaluation Centers

- **Con-TEC**
  Concentrator Technology Evaluation Center
- **Module-TEC**
  Module Technology Evaluation Center
- **PV-TEC®**
  Photovoltaic Technology Evaluation Center

Module-TEC: Technological Evaluation Center Officially Re-Opened

Fraunhofer ISE has been developing and testing new product ideas for the PV sector for more than 40 years. In February 2024, the institute opened its newly conceived Module-TEC. Prototypes up to small series can be produced with industrial equipment and tested in this PV module development and production environment, with a floor area exceeding 1 000 square meters. With this new Module-TEC, the ISE particularly aims to support European materials, module, and system manufacturers in the market introduction of technologically excellent and sustainable PV products.

Short innovation cycles and new application fields demand rapid design changes in photovoltaic modules. To be successful in this dynamically growing and volatile market, it is necessary to always mirror the current state of the art, to test efficiently and to quickly transform innovations into new products. Thanks to years of cooperation with leading equipment and materials producers from the entire PV value chain, we at Fraunhofer ISE draw on a wide spectrum of knowledge and experience. In Module-TEC, we can develop new PV module technologies, using industrial equipment for cell interconnection, laminators, and a large selection of materials and solar cell technologies. Furthermore, the infrastructure provides tools for analysis and evaluation.

High Flexibility

By cooperating with TestLab PV Modules, we at Module-TEC are in a position to implement a great range of module dimensions and designs, whereby each module can be designed individually, if required. Our interdisciplinary team accompanies developments with work ranging from virtual analysis, through joint design development, prototype construction, and manufacturing of small series, up to the evaluation of long-term stability. Very diverse configurations can be implemented in a short time due to the large selection of contacting technologies and module materials (solar cells, glass covers, encapsulation materials, back sheets, connectors, etc.) Efficient internal workflows together with accredited test laboratories allow us to carry out the development of new modules and their certification in parallel.

The new Module-TEC – illustrated here with a photo from the opening ceremony – supports manufacturers in the development of PV modules up to commercial maturity. The autoclave in the foreground enables 3D lamination of curved PV modules. The photo on the right shows one of several stringers, with which cells of all widely used formats can be connected.

Center for Electrical Energy Storage Officially Opened

Batteries are a central component for the success of the energy transformation – be it to electrify transport or to stabilize the electricity grid. Fraunhofer ISE has been conducting research along the complete battery value chain for many years. The new Center for Electrical Energy Storage, which was officially opened in October 2024, is a laboratory designed for international cutting-edge research. Our aim is to use it to strengthen the competitiveness of Germany as a manufacturing nation and to contribute to the success of the energy transformation.

In Focus: Sustainability, Safety, Performance

Together with our industrial partners, we are advancing the development of sustainable and safe high-performance energy storage units. In the new research center with a laboratory floor area of about 3700 m², we offer extremely modern manufacturing and characterization equipment for all stages of the battery value chain. In addition to the facilities that are available in the laboratories, our scientists have comprehensive competence in the fields of simulation, technological assessment, and data management. We obtain the results for our various services in different laboratories.

Battery Materials and Cell Production Lab

We develop processes for industrial clients at the laboratory scale and help them with upscaling to pilot production scale and further optimization. We concentrate on sustainable processes such as dry coating or the development and application of mini-environments to further reduce the production costs of battery cells.

Characterization and Post-Mortem Analysis Lab

We conduct comprehensive materials and post-mortem analyses. In this way, we can, e.g., identify the causes of performance problems or outages and significantly increase the safety of battery cells. Our equipment allows us to work in an inert atmosphere, from opening the cell through to analysis.

Battery Engineering, Production, and Testing Lab

We address optimized cell formation and adapted electrical and thermal characterization of batteries, and also optimized temperature control, aging modeling, prototype construction, 2nd-life storage units, innovative rapid charging technologies, and destructive and non-destructive safety investigations.

Around 100 guests from politics, industry, and science attended the official opening ceremony of the new Center for Electrical Energy Storage.

Energy Storage Application and Innovation Lab

Thanks to our laboratory equipment, we can model storage-supported energy systems and control them with the help of energy management systems. With this facility, we offer our partners an optimal environment to develop and qualify management strategies for storage systems.

The center was funded by the German Federal Ministry of Education and Research (BMBF) and the Ministry for Economic Affairs, Labor and Tourism of the State of Baden-Württemberg, which each contributed nine million euros. The building itself also serves research purposes as a living lab: within the Haid-Power project, which is funded by the State of Baden-Württemberg with three million euros, the center was equipped with a modular hybrid battery storage unit with a capacity of 836 kWh, which supports the power supply for the building, together with an 850-kW photovoltaic system on the flat roof. Thus, battery-supported solutions for commercial and industrial applications and new operating strategies can be tested under real operating conditions.

Test stand for the characterization of compressors for cooling circuits in heat pumps and chillers.

Accredited Laboratories

CalLab
PV Cells

Silicon, Thin-Film, Perovskite, Organic Solar Cells
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Multi-Junction and Concentrator Cells
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Calibration of Solar Cells

In CalLab PV Cells, we offer the calibration of solar cells from a diverse range of PV technologies. The laboratory is accredited with the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body) and counts as one of the internationally leading photovoltaic calibration laboratories. In cooperation with photovoltaic 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 develop methods to measure new solar cell technologies accurately.

In recent years, we have further expanded our measurement facilities and can thus determine realistic performance parameters for perovskite-based solar cells. In current work, calibration is extended to include large-area multi-junction solar cells with more than two pn junctions. 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.

Calibration of PV Modules

CalLab PV Modules is the only accredited calibration laboratory for photovoltaic modules in Germany. With an international record measurement uncertainty of only 1.1 % for monofacial PV modules, confirmed by the Deutsche Akkreditierungsstelle DAkkS (German Accreditation Body), we calibrate reference modules and serve module manufacturers and project developers as one of the most important reference laboratories. In autumn 2024, we reached a milestone by reducing the measurement uncertainty for large-area, bifacial modules to 1.4 %. Regular interlaboratory comparisons, including those with the Physikalisch-Technische Bundesanstalt (PTB – German National Metrology Institute), guarantee highest reliability and confirm excellent agreement.

A further distinguishing feature of CalLab PV Modules and a central element in validating the measurement results is the proven stable calibration level over many years. This also allows us to statistically analyze long-term trends with regard to essential performance characteristics and to trace changes. For example, in 2024, we identified a significant trend toward negative deviations between the rated power (the manufacturer's declared value) and the actually measured power and were able to alert the PV market to this relevant topic.

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.

CalLab
PV Modules

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TestLab
PV Modules

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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 extending 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.

Characterization of Façades and Building Components

In TestLab Solar Façades, we characterize transparent, translucent, and opaque materials, test building envelope components and evaluate the energy-relevant thermal and optical properties of complete façades. With our expertise, we support manufacturers, building planners, architects, and builders in optimizing building envelopes and developing new façade components.

We draw on extensive research experience in the following application areas:

- architectural glazing
- solar-shading systems
- building-integrated photovoltaics (BIPV)
- building-integrated solar thermal energy (BIST)

TestLab Solar Façades is accredited according to EN ISO/IEC 17025:2018 for determining transmittance, reflectance, g value, and U value by measurement and calculation. In addition, TestLab Solar Façades is recognized as a notified body of the Deutsches Institut für Bautechnik (DIBt – German Institute for Building Technology) and is thus authorized to test building products with regard to energy economy. We have specialized in architectural glazing. Fraunhofer ISE is also the European Regional Data Aggregator (RDA) for the North American National Fenestration Rating Council (NFRC). We support German and European manufacturers of building envelope products who intend to address the North American market with their products. We also offer our testing services for materials that are not directly related to building envelopes, e.g. concrete pavers (solar reflectance index – SRI) or thermal insulation (U value).

TestLab
Solar Façades

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TestLab
Solar Thermal Systems

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Testing of Collectors, Storage Tanks, and Systems

The portfolio of the accredited TestLab Solar Thermal Systems covers testing 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 this service for 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 program.

TestLab
Heat Pumps and Chillers

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Measurement and Testing of Heat Pumps and Chillers

In the TestLab Heat Pumps and Chillers, which is accredited according to ISO/IEC 17025:2018, 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 numerous operating conditions with different heat transfer media (air, water, brine). In addition to electrically driven systems, equipment driven by heat, natural gas, or test gas can also be measured.

In addition to performance and efficiency measurements, we also conduct acoustic and vibration measurements. The TestLab is listed as a testing laboratory by DIN CERTCO, BRE, RI.SE, und COCH for Heat Pump KEYMARK measurement and is also approved by the European Heat Pump Association (EHPA) to conduct the tests for the EHPA quality mark. We are actively involved in refining testing procedures and standards within international working groups. In addition to the measurements and tests according to common standards and regulations, we also offer customized measurements, including hardware-in-the-loop system configurations.

The laboratory is equipped with an integrated safety concept which allows components and systems with flammable refrigerants or ammonia to be measured. Air-water or brine-water heat pumps can be measured up to a heating or cooling power of 75 kW at air temperatures from –25 °C to 50 °C and water or brine temperatures from –25 °C to 95 °C.

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 MW. Our staff can draw on the extensive equipment of the Center for Power Electronics and Sustainable Grids. Furthermore, the laboratory equipment enables us to test the electric properties of inverter systems, characterize them according to current grid connection regulations and carry out climatic-chamber tests according to the 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. 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 electronics equipment with high accuracy.

TestLab
Power Electronics

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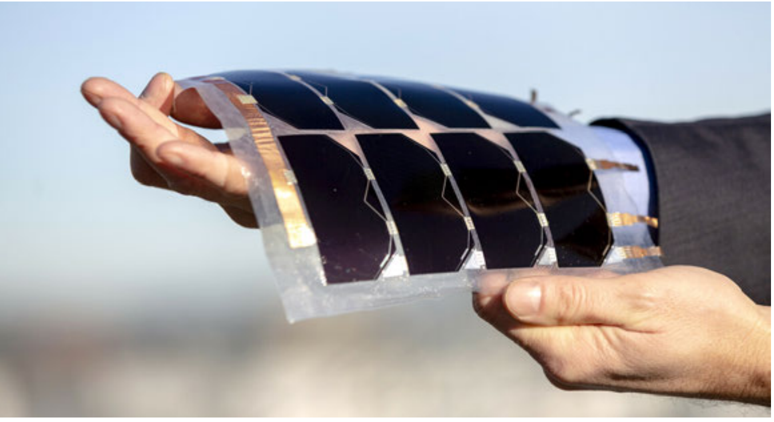
Highlights of Our Research

The logo of the Sustainable Development Goals of the United Nations highlights those contributions that are particularly relevant to sustainability aspects.

III-V Photovoltaics: from Space to Earth



Extremely light module of highly efficient III-V multi-junction solar cells.

III-V multi-junction solar cells have supplied electricity reliably for more than 20 years to satellites in space, achieving the highest efficiencies of all photovoltaic technologies. Two to six subcells of III-V compound semiconductors or germanium are stacked on top of each other in order to optimally convert sunlight in all spectral ranges (visible to infrared). These multi-junction or tandem solar cells are highly efficient, robust, and very stable. However, they have not been successful yet in the terrestrial mass market as material and production costs are more than two orders of magnitude higher than those of the current standard solar cells. The high costs are distributed equally among production of the germanium substrates, epitaxy of the III-V semiconductor layers, and processing of the wafers into solar cells.

Today's solar cell production applies well-established processes from the microelectronic or optoelectronic industries and is based on processes with a low throughput, starting with raw materials, some of which are expensive. This could change in future if we succeed in transferring some of the innovations from silicon cell production to III-V multi-junction solar cells without affecting the efficiency of the cells. We are actually working on reusable germanium substrates which allow repeated growth of III-V layers. After epitaxy, we separate the thin absorber layers, which are only a few micrometers thick, from the substrate and process these into extremely thin, flexible thin-film solar cells. In doing so, we use less expensive metals such as copper and apply processes such as electroplating, spraying, sputtering, or inkjet printing to replace classic photolithography and the evaporation of metals.

To reduce the costs of epitaxy further, we cooperate with partners from the industry to develop new high-throughput equipment for metal-organic vapor phase epitaxy. This is intended to reduce processing times from several hours to only a few minutes. If these developments were combined, then III-V multi-junction solar cells could be manufactured at significantly lower costs in the future. This would open new markets in space for applications in near-earth orbits and also markets, e. g. in the car sector. III-V multi-junction solar cells can offer added value wherever high efficiency is particularly advantageous. In countries with high direct solar irradiance, the cells are also used under 500 to 1000 times concentrated sunlight in so-called concentrating photovoltaics. Here also, the production costs for the solar cells represent a significant component of the financial viability, which we intend to improve appreciably during the next few years. Then III-V multi-junction solar cells would not only be competitive in space but also for terrestrial PV applications.

Micro-CPV modules achieve efficiencies exceeding 36 % and are thus the most efficient photovoltaic technology in the world.

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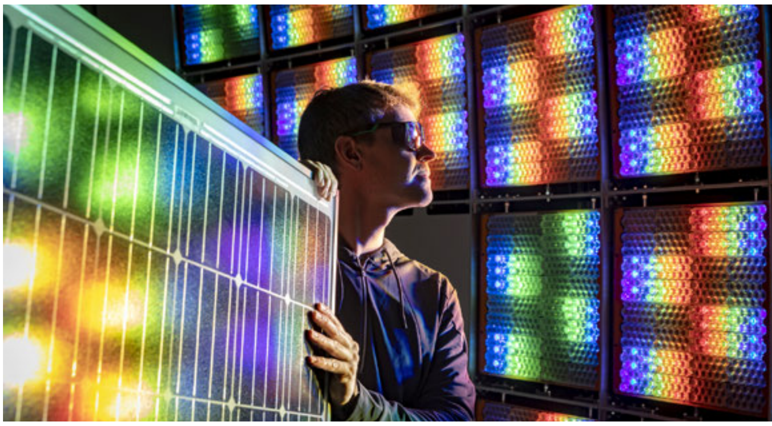
Perovskite-Silicon Tandem Photovoltaics: from Cell Development to Certified Module

The perovskite-silicon tandem solar cell is considered to be a promising solar cell concept which is progressing toward commercial maturity and is currently attracting considerable international attention. The fundamentally simple manufacturing processes as well as the excellent optical and electronic properties of the perovskite semiconductor enable not only highest efficiencies but also favorable production costs. At Fraunhofer ISE, we are working on the complete development chain for perovskite-silicon tandem photovoltaics, from materials through solar cells up to modules.

In cell development, we are focusing on process technologies that can be implemented industrially, enabling rapid transfer from the laboratory to a production environment. A central development is the deposition of the perovskite absorber by the two-stage hybrid method. Applying this method, we have already achieved a certified record efficiency of 31.6 % on the laboratory scale. In the "LiverPool" and "Pero-Si-SCALE" projects, we are developing potential high-throughput processes to deposit inexpensive and efficient perovskite absorbers onto textured silicon by vacuum deposition and wet chemical processes.

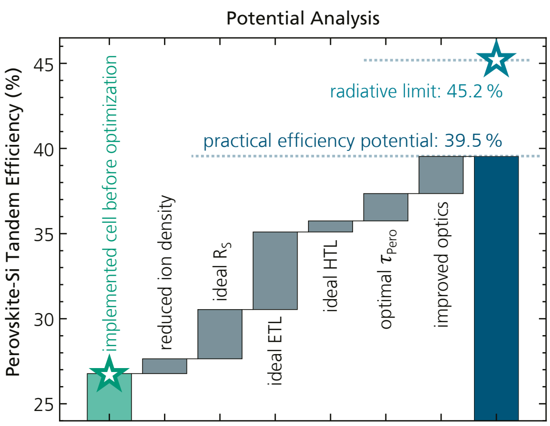
Close interaction between technological development and characterization and simulation means that we can analyze the specific losses in our tandem solar cells. We can analyze the cells highly accurately by applying a combination of widely diverse characterization methods, such as spectrally resolved photoluminescence to analyze material and interface properties, Suns-Voc measurements, and current-voltage metrics. By carrying out advanced optoelectronic simulations and comparing these results with measured data, the individual loss channels in the cell can be quantified and targeted optimization strategies can be developed (see figure below).



LED module simulator to characterize and certify large-area tandem photovoltaic modules.

In addition to cell development, the development of module technologies, module analysis, and module certification represent decisive success factors for commercially introducing perovskite-silicon tandem photovoltaics. Together with industrial partners, we have successfully developed processes to connect and encapsulate perovskite-silicon tandem solar cells and have developed and produced industrially relevant modules. We had to develop low-temperature processes for the temperature-sensitive perovskite cell which preserve the cell and simultaneously are suited for industrial mass production. Subsequently, we measured the produced modules by applying the measurement routines that had been developed for an LED solar simulator in the "KATANA" project (see figure).

With this portfolio and our expertise in transforming laboratory results into industrially relevant processes, we are in a good position to continue the transfer of perovskite-silicon tandem solar cell technology to industrial production.



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

Optoelectronic simulation of a perovskite-silicon tandem cell, its cumulative loss channels and their respective efficiency gains toward the practical efficiency potential of 39.5 %.

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Scaling of Technologies for Perovskite-Silicon Tandem Solar Cells

Solar cells made of silicon wafers by applying high-temperature processes were and still are the dominant cell structures on the global photovoltaic market. Although still further increases in efficiency are to be expected in the coming years, we are reaching the practical and physical limits for the silicon solar cell. However, to use resources efficiently, it is necessary to achieve a further increase in efficiency beyond the silicon limit. Tandem solar cells are considered to have the greatest chance of success as the technology to succeed silicon. In addition to III-V and perovskite tandem concepts, we at Fraunhofer ISE consider that the perovskite-silicon tandem solar cell is a good candidate.

The perovskite-silicon tandem solar cell is based directly on the well-established silicon cell technology. To use it as the bottom cell of a tandem stack, we had to address additional developmental steps in our research: In the "EpoPOC" and "RIESEN" projects, we at Fraunhofer ISE have thus investigated how solar cells that are based on the so-called TOPCon process need to be adapted. In particular, the very stringent requirements on particle-free surfaces were identified as a major challenge. Similarly, depositing the metal contacts on the back of the cell is a process sequence that can be problematic. Both challenges are caused by the fact that the perovskite-silicon tandem solar cell technology combines a high-temperature wafer technology with a low-temperature thin-film technology. By applying an industrially very relevant process, developed by us, for the TOPCon bottom cell, we produced a tandem solar cell with an efficiency of 27.3 %.

The top cell, which is less than one micrometer thin, consists of several-nanometer-thick layers that are deposited directly onto the bottom cell, either from solution or by vacuum processes. For the deposition of the perovskite absorber, we at Fraunhofer ISE are researching a so-called hybrid process that combines both coating methods. This approach allows us to deposit the perovskite top cell onto industrially textured silicon bottom cells parallel to the textured surface and thus to achieve higher efficiencies and energy yields. In the "PrEsto", "LiverPool", and "MaNiTU" projects, we proved that an evaporated scaffold of inorganic components that is infiltrated with a solution of organic components gives the best results on textured surfaces. We achieved a certified efficiency of 31.6 % with this hybrid approach. In particular, we successfully scaled the solution-based coating both with a dispensing process and also by spray coating.

The Pero-Si-SCALE laboratory at Fraunhofer ISE is currently being established as a platform in which we will be able to operate all of the facilities needed for the production of perovskite top cells in a single large laboratory. This will be based on the wafer standard of the Si photovoltaic industry of 210 × 210 mm^2 and will allow small series of 50 wafers per day to be processed. In this way, we will be well equipped to advance applied research on the perovskite-silicon tandem solar cell on the pilot production scale and to support the European industry in the development of materials, equipment, and processes to produce disruptive photovoltaic products.

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

A large-area perovskite-silicon tandem solar cell, produced at Fraunhofer ISE.

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Developing Perovskite-Perovskite Tandem Solar Cells with Higher Efficiencies

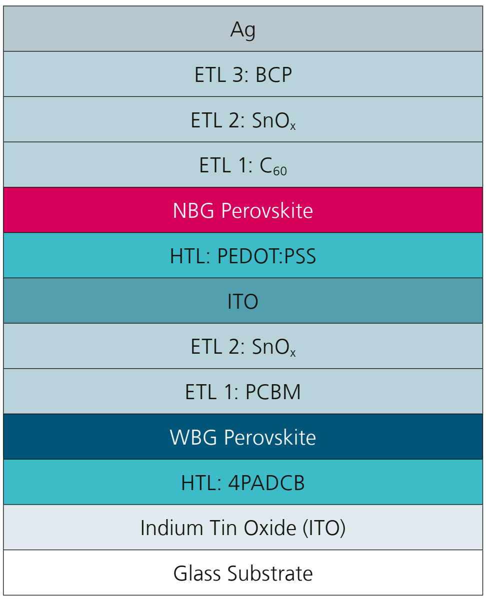
With our research work on tandem photovoltaics, we aim to achieve higher efficiencies for solar cells and to increase the electricity yield per area. New materials such as perovskites help us to develop very-high-efficiency solar cells. For example, we were able to demonstrate that the combination of two perovskite absorber materials with different band gaps leads to higher efficiencies. As is also the case for perovskite-silicon tandem solar cells, this is because the thermalization losses are reduced, meaning that photons with higher energy are converted more efficiently into electricity.

An advantage of purely perovskite-based tandem solar cells is that they can be processed at low temperatures, such that they can be produced in a continuous roll-to-roll process on flexible substrates. Potentially, this enables very low production costs. For the subcell with the narrower band gap that is positioned further from the light source, perovskites based on lead-tin mixtures, corresponding to the state of the art (here $FA_{0.7}MA_{0.3}Pb_{0.5}Sn_{0.5}I_3$) are used, which allow band gaps down to about 1.2 eV. For this reason, a perovskite with a band gap of 1.75 to 1.77 eV is used for the subcell that is directly exposed to the light source. Here, we use $Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$. In the following paragraphs, we will describe how the devices are optimized.

Our first step consisted of finding an alternative to the previously used PEDOT:PSS layer, which functions as a hole transport layer for the perovskite with the narrow band gap. It became evident that a new PEDOT:PSS formulation, which is free of water and has a lower PSS content, leads to a slightly increased open circuit voltage and to a significantly increased fill factor. As a result, the efficiency was improved from around 20 % to 23 %.

Mixtures of halogenides are applied to obtain perovskites with a wider band gap. However, this often leads to a stability problem, as the two halogenides segregate and form domains that are rich in iodide or bromide, which in turn cause the voltage of the solar cell to become lower. Experiments demonstrated that this effect can be suppressed by an alkyl amine additive, such that the stability of the perovskite with the wider band gap was improved.

Nevertheless, the values of the open circuit voltage of the perovskite solar cells with wider band gaps were still too low. Among other effects, the interface of the absorber with the electron transport layer proved to be responsible for this. For this reason, we investigated various passivation approaches in a further series of experiments and identified a propane diammonium iodide as a highly suitable material. This enabled us to increase the open circuit voltage and the fill factor appreciably, which was then reflected in an improvement of the efficiency for single solar cells with a wide band gap from 16.5 % to 19 %.



Schematic configuration of a perovskite tandem solar cell. HTL stands for hole transport layer, ETL for electron transport layer, WBG for wide band gap, and NBG for narrow band gap.

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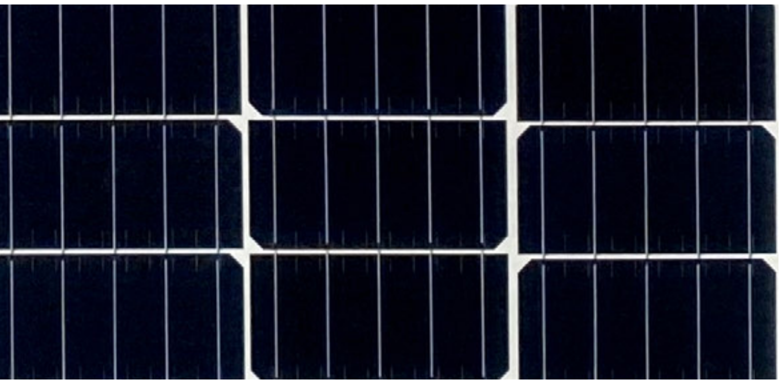
Production of TOPCon Solar Cells and Modules with M10 Wafers

Silicon solar cells with passivating contacts, particularly the TOPCon technology (Tunnel Oxide Passivated Contact) that was developed at Fraunhofer ISE, now represent the dominating cell architecture for industrial production due to its high efficiency. At present, there is a transition to larger wafers, with the goal of lowering the specific production costs. Responding to this trend, we have further developed the production process at Fraunhofer ISE: We are now the first European research institute able to process industrial-scale M10 wafers (edge length: 182 mm) in our PV-TEC pilot line laboratory. TOPCon solar cells, which had been processed exclusively in large industrial facilities, very quickly achieved efficiency values of currently 24 % with this wafer size (solar cell area 330.3 cm^2; independently measured at the ISFH CalTec calibration laboratory). The n-doped polycrystalline Si layer is only 80 nm thick. It is notable that metallization deposited by light-assisted electroplating resulted in the same efficiency as the usually applied flatbed screen-printing process. The throughput of about 100 wafers per hour on each machine allows our clients to benchmark their production equipment, their materials, and other products on a pilot line with the potential for high efficiency.

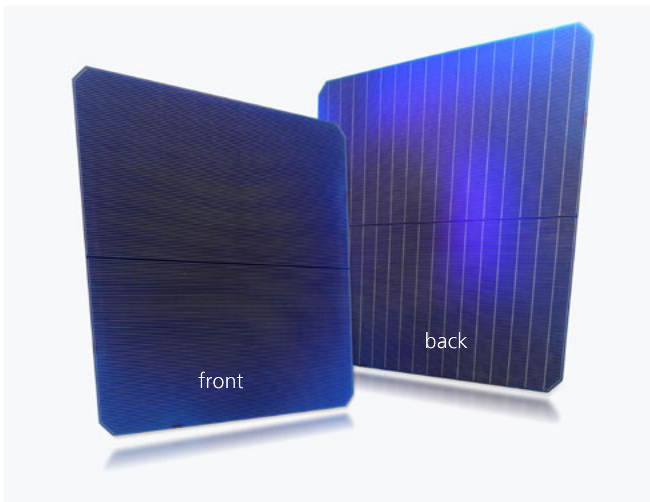
In addition to cell development, we are conducting research on module technology. Large industrial production lines are available to produce full-size modules in our Module-TEC production laboratory. In particular, the development of low-loss circuits and the development of reliable and stable encapsulation of the solar cells is playing an important role here. A full-size module consisting of 120 half-cells was made using only TOPCon solar cells with an edge length of 156.75 mm which had been produced at Fraunhofer ISE. The metallization of the solar cells is a special feature as it consists only of thin contact fingers without busbars, meaning that the amount of silver needed can be reduced. To contact the solar cells, we have used electrically conductive adhesives instead of the soldering process that is usual in industrial module production. As the cells do not have any busbars, the interconnectors contact the thin metal fingers directly. The module current was increased by initial process optimization such that the cell-to-module power conversion factor (CTMPower) was increased to 99 %. The module successfully passed a thermal cycling test with 200 cycles.

In future, we will concentrate on further developing the individual processes and using larger TOPCon cells with higher efficiency, which are produced at our institute.



Full-size module that was produced at Fraunhofer ISE. The cell connectors are connected directly to the contact fingers with a conductive adhesive.

Front and back of a bifacial TOPCon solar cell produced from a M10 wafer in PV-TEC at Fraunhofer ISE.



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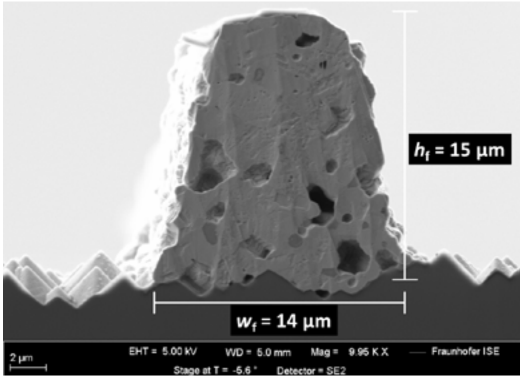
Solar Cell Production: Minimal Contact Structure Widths Increase Efficiency and Reduce Material Costs

In modern solar cell production, precise and cost-efficient processes to produce contact structures are very important, particularly to implement the finest possible metal contacts on the front of the solar cell. At Fraunhofer ISE, we apply innovative laser and printing technologies to achieve minimal contact structure widths.

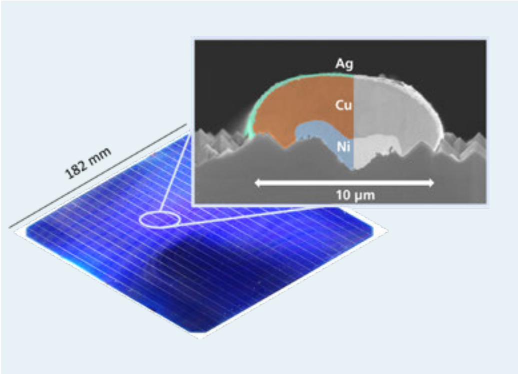
In our PV-TEC Back-End pilot production laboratory, we apply different printing technologies. These include classic screen printing as well as innovative approaches such as extrusion with multi-nozzle dispensing printing heads, a technology that we are continually developing further with our spin-off, Highline Technology. Both technologies enable contact widths in the order of 15 µm, whereby the dispensing technology allows 10 % to 20 % better usage of the printed metal (e. g. silver) due to the very homogeneous contact form. In addition, we have implemented and patented a new printing process called FlexTrail, which allows different materials to be printed with structure widths in the order of 10 µm. Special flexible glass capillaries, which we also developed at the institute, are used in this process. At present, our R&D work is focusing on the use of copper instead of silver-containing media. We aim to significantly lower the material costs in this way, without reducing the efficiency of the solar cells.

In the laser technology sector, we apply various laser processes to create finest structure dimensions in the order of 5 µm when opening dielectric layers. This is decisive for the subsequent electroplating processes, in which very fine metal contacts with structure widths in the order of 10 to 15 µm are created. The realized metal contacts consist primarily of copper; in general, only thin layers of nickel to contact the silicon and silver as a protective layer on the contact surface area are needed. Consequently, electroplating processes allow the expensive silver to be replaced almost completely. As an alternative to laser processes, we are also developing inkjet processes for local definition of electroplating contacts (Mask&Plate approach).

A current, highly relevant research area, where we combine our competence on both laser and printing technologies, is the use of laser processes to produce highly precise screen-printing forms with minimal opening widths.



Scanning electron micrograph of a screen-printed fine-line contact.



Detail of an electroplated fine-line contact.

The technological solutions presented here demonstrate multifaceted approaches to reduce contact widths to the range from 10 to 20 µm. Creation of such fine structure widths not only leads to higher efficiencies due to reduced shading of sunlight by the contacts but also results in significant material savings of expensive metals such as silver, an important aspect contributing to the sustainable production of solar cells.

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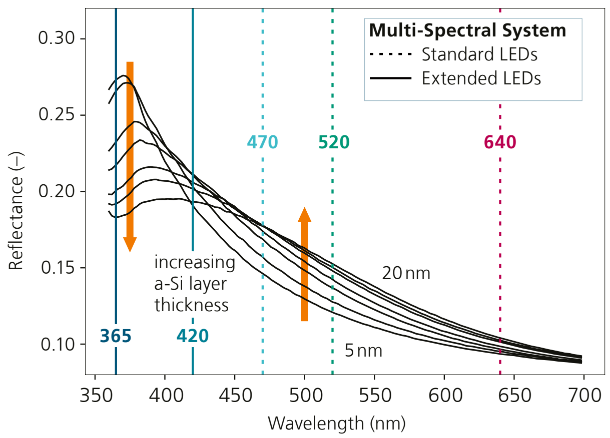
Spatially Resolved, Quantitative Inline-Analysis of Thin Functional Layers Based on Multi-Spectral Images

High-efficiency solar cell technologies such as silicon heterojunction (SHJ) technology are becoming increasingly important for mass production. However, the high efficiency makes these technologies more sensitive to small defects and inhomogeneities. If these are identified early, processes can be readjusted quickly and defective specimens can be removed, such that the efficiency spread can be guaranteed to remain small. To do this, spatially resolved in-line measuring procedures are needed, as particularly the edge regions of wafers are susceptible to inhomogeneities. The 10-20-nm-thin layers of amorphous silicon (a-Si) represent an important structural component of SHJ technology for surface passivation and charge carrier selectivity. The thickness of these a-Si layers has a strong influence on the contact resistance (electric losses) as well as on reflection at and parasitic absorption in the layers (optical losses) and is thus an important quality parameter.



Simulation of the spectral reflectance for different a-Si layer thicknesses (textured surface). Wavelengths of the multi-spectral system with UV extension.

In the "SALSA" project, we have demonstrated that rapid measurement of thickness is possible by applying inline spectrophotometry and modeling the reflectance spectra optically (figure below, left). We also showed that high accuracy can be achieved for textured surfaces if differential reflectance is considered. As spectrophotometry only allows measurements along single traces with low spatial resolution, we have transferred the procedure to multi-spectral imaging data. These can be recorded with an inline measurement system for color inspection produced by our partner ISRA Vision, at up to five wavelengths in a measurement time of less than 1 s (figure below, right). Careful observation of the reflection behavior of a-Si layers of differing thickness revealed that the reflectance in the UV range reacts most sensitively to the layer thickness, and inversely in the blue range, which is why the standard measurement system was extended by two wavelengths at 365 and 420 nm (figure below, left). The figure below, right illustrates, after calibration of the gray-value images, there are thus five reflectance values available in every pixel that can be modeled optically very well, so that a thickness topography can be derived from the five images. The thicknesses that were determined with the multi-spectral fit agree very well with reference values from spectral ellipsometry, as is shown for a sample with deliberate variation of the a-Si thickness.

This demonstrates that it is possible to obtain spatially resolved measurements of the a-Si layer thicknesses from multi-spectral data. With the help of theory-guided machine learning procedures, the complex modeling can be accelerated to the necessary rate of only seconds per measurement. This means that an inexpensive inline measurement technology and analytical procedure are now available for new production lines, which can also be transferred to other functional layers.

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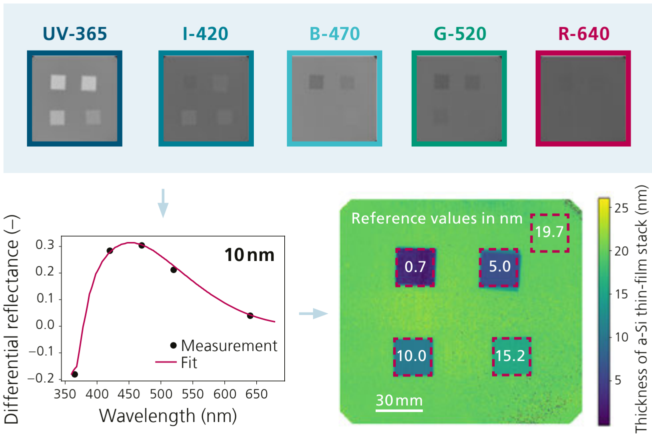

Silicon wafer with a-Si layer thickness variation: multi-spectral images (above), individual pixel reflectance values with optical modeling (left), layer thickness topography (right).

Perspectives for PV Recycling in Germany

Over the past decades, the installed PV capacity in Germany has increased enormously: In 2023, the installed PV power in Germany amounted to 82 GWp. Although this is a positive development on the one hand, on the other hand, photovoltaics produces an appreciable amount of waste as some modules are replaced already after 20 years of service. A circular economy is needed in order to provide low-CO_2 electricity from solar energy and conserve resources in the long term. At present, more than 10 000 tonnes of old photovoltaic modules are introduced into the recycling market in Germany every year. Due to the increasing installation of PV modules, we expect that there will be more than 500 000 tonnes per year from 2030 onward. As PV modules contain valuable materials, it is highly logical to recycle them as part of a sustainable economy. However, effective recycling processes are still becoming established.

At Fraunhofer CSP in Halle/Saale, we have developed an innovative recycling process that allows the extraction of silver from solar cells and purification of the silicon, so that new silicon crystals can be produced from 100 % recycled silicon. These crystals were processed into wafers and used for the production of PERC cells with a maximum efficiency of 19.7 %. An overview of the materials that were used in installed PV modules shows that they contain an appreciable amount of valuable raw materials, particularly silver and silicon.

According to the EU Directive 2012/19/EU "Waste from Electrical and Electronic Equipment" (WEEE Directive), more than 80 % of the materials must be recycled. The legal requirements are often met by recycling the aluminum frame and the glass cover, while other materials that are present in smaller quantities are not regained.

During our recycling process, the PV modules are mechanically shredded and sorted according to particle size, conductivity, and density. As part of our research work, we treated a total of 627 kg of broken cells from end-of-life PV modules; after demetallization, 547 kg of silicon and 6.18 kg of metallic silver were extracted. After etching away the emitter from the purified silicon, 370 kg of pure silicon remained.

We processed the ingot into wafers, from which our colleagues at Fraunhofer ISE in Freiburg produced PERC solar cells. Finally, we mounted these solar cells in a demonstration solar module, which is currently installed at the test field of our premises in Halle/Saale. The wafers had a base resistance of around $\rho_{Si} = 0.5$ to $1\,\Omega\,\text{cm}$, the thickness of the wafers was 180 m, the M2 wafer format was used, and the wafers had each been subjected to alkaline structuring. The efficiency of the cells reached values of up to 19.7 %.

The results show that silver can be extracted from old PV modules and silicon can be purified such that new solar cells can be produced. This increases the recycling quota and allows valuable raw materials to be regained.

The results were obtained within the projects "ReModul", funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), and "Apollo", funded by the European Union.

Material	Mass (t)	Total value (Mio. €)	Proportion of the total value (%)
Glass	3 400 000	170	6.0
Aluminium	624 000	1 060	37.7
Polymers	480 000	–	–
Silicon	144 000	288	10.2
Copper	24 000	108	3.8
Silver	1 700	1 190	42.3

PV modules contain various raw materials, which are listed in the table and classified according to mass, total value, and proportion of the total value of the raw materials.

Cz crystal produced from 100 % recycled silicon.

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Outdoor Performance Lab – Testing and Evaluating PV Modules under Real Conditions

Occupied and vacant measurement positions for single modules at the test field of Fraunhofer ISE in Merdingen.

Photovoltaic modules and systems offer an appreciable potential for further innovations and optimization. An important factor to achieve this is the testing and evaluation of new technologies. We can offer these R&D services in our Outdoor Performance Lab: Here, we test PV modules under real conditions and evaluate their long-term stability to guarantee reliable and efficient electricity generation and to increase investment security. At present, around ten different measurement projects are running at the Outdoor Performance Lab, both as direct commissions from industry and also as projects with (a share of) public funding.

An important focus is on the benchmarking of PV modules with different cell technologies. We determine their performance and the reliability of the modules in continuous open-air measurements and specific tests of shading tolerance. This data is decisive for market acceptance and investment security for new module technologies. The modules are tested under differing environmental conditions and compared to different references, to validate their performance and reliability. This includes tests in different mounting or integration situations and under differing climatic conditions at our test sites in Merdingen near Freiburg, on Gran Canaria, and in the Negev Desert. In doing so, an important aspect is to reduce measurement uncertainty in the module characterization as far as possible. We meet this challenge by developing and combining accurate measurement methods both in the laboratory and at the test site.

Our investigations are not restricted to PV modules. Under the heading of "Integrated Photovoltaics", we also measure applications in vehicle components, roof structures, noise barriers, building envelopes, and other structures. Similarly, we are also involved in optimizing new application fields such as agrivoltaics and floating PV power plants.

In the "MiMoRisk" project, we focus on the development of models that describe specific degradation kinetics for individual technologies or module types. These models allow the long-term yields and yield risks to be predicted accurately and thus the planning and operation of PV systems to be optimized. By integrating these models into software-assisted tools, we can further increase the accuracy of the yield predictions and minimize risks for the PV industry. This increases planning security and supports the insurance of PV systems, as accurate predictions of the yield development and the associated risks are decisive for the economic viability of the systems.

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

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Mounting racks for bifacial PV modules, which can be adapted to all module formats and frame sizes, without shading the back of the modules.

Accompanying and Supporting the Market Launch of Agrivoltaics in Germany

Agrivoltaics enables the simultaneous generation of renewable electricity and agricultural production on the same area; as such, it is a key technology to alleviate competition for land areas. We are accompanying the national German market launch within the "SynAgri-PV" project. Together with an interdisciplinary consortium of ten partners, we are pursuing the goals of evaluating boundary conditions relating to nature conservation, the law, economic viability, and social parameters, and identifying areas needing action.

The interactive map in our database provides an overview of the agrivoltaic systems in Germany (www.agri-pv.org/en/). Of the total of 18 completely documented systems, nine are located in arable farming, seven in horticulture, and two in permanent grassland (see table). System operators and owners can fill out a questionnaire to complete the database.

The variety of agrivoltaic systems can be experienced with the help of our virtual demonstrator (see figure), which we have already presented at several different events, e.g. at AgriVoltaics 2024 in Denver, CO. The visualization of four different agrivoltaic applications and their integration into an agricultural landscape of the future provides a basis for discussion and is intended to encourage acceptance of the technology in a playful manner.

Together with the Leibniz Centre for Agricultural Landscape Research (ZALF), we organized the second "Nationales Forum Agri-PV" (German National Forum on Agrivoltaics) at the Fraunhofer-Forum Berlin in May 2024. The forum provided an opportunity to discuss the provisional German standard, DIN SPEC 91492, which had been published shortly beforehand. It specifies the requirements on agrivoltaics for animal husbandry and distinguishes it from ground-mounted PV.

Type of system	Number (n)	Installed power (kW_p)	Average installed power (kW_p/n)
Data from complete questionnaires	**18**	13 047	767
Permanent grasslands	2	2 422	1 211
Horticulture	7	1 160	166
Arable farming	9	9 508	1 056
Data from incomplete questionnaires	9	38 526	4 281
Total	**27**	51 573	1 433

Overview of the various types of agrivoltaic systems in Germany (status as of April 2024). The data are continually extended and updated under https://agri-pv.org/en/community/agrivoltaic-facilities-in-germany/

It complements the DIN SPEC 91434, which defines the general requirements for primary agricultural use. Given the references to the first provisional standard in the German Renewable Energy Act and building code, it remains to be seen whether DIN SPEC 91492 will similarly serve as a basis for the market introduction of agrivoltaics in combination with animal husbandry. Furthermore, it is currently being debated whether the DIN SPEC 91434, which is already three years old, should be further developed to become a regular standard. We aim to establish the Forum as a permanent platform for exchange.

Within the "SynAgri-PV" project, we aim to support sustainable and synergetic integration of agrivoltaics into agriculture with networking activities and by accompanying the market launch. In this way, we contribute to the successful transformation of the agricultural and energy sectors.

With the virtual demonstrator, an elevated agrivoltaic system can be tested with special crops.

The SynAgri-PV project was funded by the German Federal Ministry of Education and Research (BMBF).

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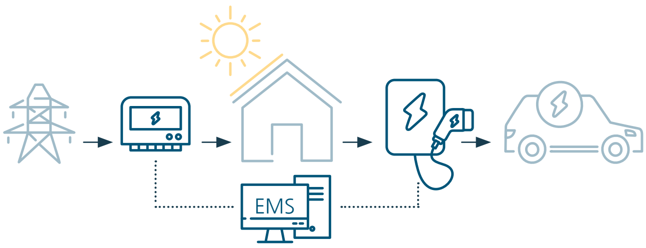
"Wallbox-Inspektion" Project: Test Procedures for Solar and Grid-Supportive Charging of Electric Vehicles

Storing your own solar electricity in an electric vehicle, later using it in the household and supporting the electricity grid while doing so – this solution sounds promising. We aim to support this development in our "Wallbox-Inspektion" project by researching new procedures that evaluate the quality of unidirectional and bidirectional charging solutions for privately charged electric vehicles. In time, we want to establish an industrial standard. A quality comparison is at the center of our testing procedure, which encompasses the evaluation of efficiency and the control quality for smart solar charging and bidirectional charging.



Complete system for the "Wallbox-Inspektion" tests, including the electricity meter, the energy management system, and the charging station.

Smart solar charging means that a car is predominantly charged with self-generated electricity from the PV system and, while doing so, supports the electricity grid. As the electricity generation fluctuates according to the weather conditions and household consumption, it is advantageous if the charging station regulates the charging current rapidly and accurately. For this reason, we have prepared a testing guideline for unidirectional solar-controlled charging, which describes the test procedures for determining the standby consumption, the control quality, and the switching between single-phase and three-phase charging, among other aspects. The test objects are solar-controlled charging solutions for domestic use, consisting of the charging station itself, an energy management system, and a dedicated electricity meter. The latter is installed behind the official electricity meter and measures the power at the grid connection point as the control quantity. The aim is to maximize the solar fraction of consumed electricity and thus to reduce the load on the grid.

In our Digital Grid Lab we have installed different charging solutions and tested them according to the test guidelines. For the tests, we have used the ev twin digital vehicle twin in the laboratory to model an electric vehicle including real power flows. We modeled the solar electricity generation with an electric source. This means that we have a reproducible testing environment for the charging stations which can be freely parameterized.

An essential goal of the Wallbox-Inspektion tests is to reveal potential for optimization and thus to contribute to the most efficient use of solar energy as possible. Already an initial comparison showed that the control quality is very different between the solutions. An example: If the generation of excess electricity changes considerably, it can take up to two minutes for some chargers to react by adjusting their control parameters. This quantity is decisive for making good use of the available solar radiation, as the available power fluctuates on cloudy days within the control response time. These and other results will be published in the final version of Wallbox-Inspektion under www.wallbox-inspektion.de.

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

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Test environment for charging solutions in the Digital Grid Lab with the digital electric vehicle twin, ev twin.

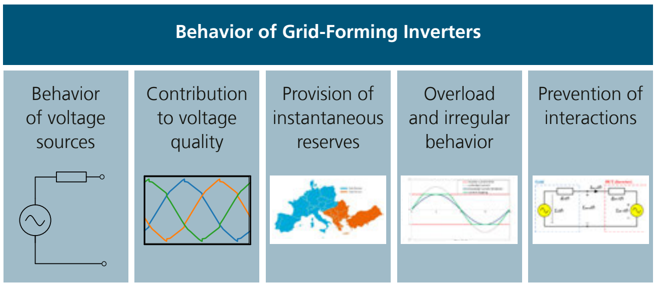
En route toward Climate Neutrality: the Role of Grid-Forming Inverters in the Future Electricity Grid

The European nations operate one of the largest machines in the world with the synchronously coupled joint electricity grid in continental Europe. It connects about 1 000 GW of installed generation capacity, which annually supplies more than 2 500 TWh of electricity to a market of more than 400 million people. Currently, more than 500 million tonnes of CO_2 emissions are produced annually due to the combustion of fossil fuels in conventional power plants. To reduce these emissions, the EU is the first continent to aim for climate neutrality by 2050. It plans almost complete decarbonization of the electricity sector by 2040 and an installed PV power of 600 GW by 2030.

Preparation of a grid-forming inverter for measurement in the Multi-Megawatt Lab.

For the energy transformation to be successful, it is not only necessary to expand renewable energy sources but also to guarantee system stability. At present, stable grid operation – in other words, the provision of grid voltage with a stable amplitude and frequency – is guaranteed almost exclusively by conventional utility-scale power plants. However, in future, also converter systems in renewable and battery storage power plants must possess grid-forming properties. This means that extremely reliable and durable converters are required, e. g. in large-scale PV power plants.

Until now, there has been a lack of guidelines on the dynamic behavior of grid-forming systems to support the power grid; also, there is no generally applicable procedure to prove the compliance of grid-forming properties. This was documented by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) in its road map on system stability



Test requirements for grid-forming inverters (schematic representation).

(Process F6, Testing principles for certification of grid-forming electricity converters). The road map formulates a timeline for secure operation of the future electricity supply system with 100 % renewable energy sources.

In the GFM-Benchmark project, we at Fraunhofer ISE are developing and testing test procedures for grid-forming inverters. The goals are to determine the actual state of the art to further develop grid-forming inverters on the basis of comparative measurements and to test and optimize black-box test procedures for further standardization activities. In future, grid-forming inverters will guarantee grid stability not only during normal operation but also during major disruptions. In the "StABIL" project, we at Fraunhofer ISE are analyzing future loads on grid-forming inverters in large PV power plants, to obtain information about the optimized design of hardware. In doing so, we are focusing on a long lifetime of the resources used, which is tested in laboratory and field tests and subsequently transferred to design regulations for PV inverters that have been optimized to achieve a long lifetime. This is our contribution to the safe and robust operation of one of the largest machines in the world.

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Sodium-Ion Batteries for the Energy Transformation

Lithium-ion batteries (LIB) are currently dominating the market for storage batteries. However, the market distribution will change in the next few years as, in addition to socio-economic and ecological problems, LIB are struggling with issues of raw material scarcity (e. g. for lithium and cobalt). As an alternative, sodium-ion battery (SIB) technology is becoming increasingly interesting as the availability of raw materials for this technology is less critical. In addition, the raw materials for SIB are less expensive and their high-temperature stability and rapid charging capacity are better. However, due to the somewhat higher voltage potential compared to lithium, the energy density of SIB is inherently lower than for LIB.

Similarly to LIB, the production processes for SIB electrodes to date have mainly relied on solution-based coating processes, which cause high costs for drying, calendering, and recovery of critical solvents. At Fraunhofer ISE, we are researching solvent-free coating technologies and the transfer of SIB technology to applications, together with partners from universities and the industry from Baden-Württemberg in the "PRONTO" and "VORAN" projects.

Precursors for active cathode materials for sodium-ion batteries are synthesized in the battery research laboratories at Fraunhofer ISE.

In "PRONTO", we are developing optimized active materials and high-performance battery cell architectures for SIB. Researchers from the Karlsruhe Institute of Technology (KIT) are responsible for developing the active materials. Based on previous experience at Fraunhofer ISE on dry processing of battery electrodes, we successfully validated porous thick-film electrodes in the millimeter range, which are many times thicker than those from the established solvent-based processes. However, challenges arise concerning the Na^+ transport processes within the battery cell. To guarantee the required performance despite the thicker film thickness, project partners from the University of Stuttgart have modeled the Na^+ transport process within the electrodes and derived recommendations for the electrode design.

In the "VORAN" project, we aim to create the prerequisites for large-scale production of SIB for stationary and mobile applications. An innovative technology platform, which we initiated together with our industrial partners, acp systems AG and Helmut Hechinger GmbH, serves as the basis. Furthermore, we cooperated with acp systems AG to validate the intended modular battery cell architecture as a component of a "design-for-recycling" concept and the feasibility of electrode structures based on dry processing on a large, application-oriented scale. Based on that, we have begun to develop recycling processes for the battery materials.

By the end of the "PRONTO" and "VORAN" projects (end of 2025 and 2026, respectively), we will further develop and upscale the process technology and material development for the SIB modules and combine these with corresponding battery system technology. Both projects represent essential steps in the direction of large-scale mass production, which the Helmut Hechinger GmbH company plans to implement.

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The PRONTO project is funded by the Baden-Württemberg Ministry of Economic Affairs, Labor and Tourism.
The VORAN project is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

NRGISE.ONE – a Product Suite for the Integrated Planning and Control of Energy Storage Units

The inclusion of one or more storage systems in an electric power supply structure consisting of generators and consumers enables manifold applications. For example, an industrial enterprise can meet its energy demand by the combination of a PV system and a battery and thus minimize its costs for electricity from the grid. This type of energy system can be planned and controlled efficiently with the help of suitable tools. In addition, the costs for the installation and operation of the systems can be optimized.

NRGISE.ONE
Integrated Product Suite

NRGISE.plan
web application + premium control + premium models

NRGISE.plan Free
open-source software + basic control + basic models

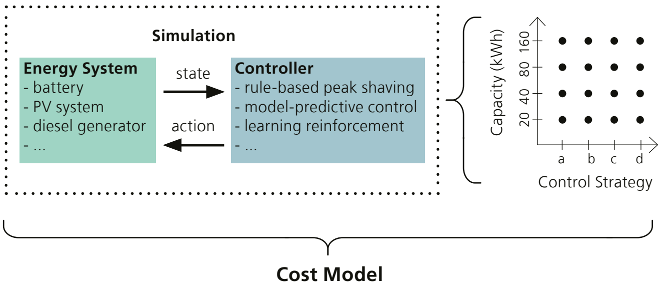
NRGISE.control
energy management system + premium control + premium models

The "NRGISE.ONE" product suite facilitates the integration of electricity storage units into an existing supply structure.

In this context, we at Fraunhofer ISE have developed the "NRGISE.ONE" product suite, which allows planners and operators of electricity storage units to achieve economically rational integration of the systems into a supply structure. As a starting point, the suite includes the "NRGISE.plan" planning software, which allows efficient design of storage-based energy systems or their components (storage units, PV system, …) on the basis of detailed system models and AI-based procedures. A user-centered design approach makes a simple planning process possible. As an extension, the software suite provides the "NRGISE.control" energy management system, which enables economically optimized operation management of the systems in the field. System control is consistent with the planning phase, as both steps draw on the same system models and optimization algorithms. This commercially unique integration of both products closes the so-called simulation-to-reality gap. In this unwanted gap, the usage of different approaches for planning and control causes significant differences to arise between the initially calculated economic returns and those that are later achieved in practice. As further added value, the AI-based optimization procedures allow multiple-purpose use of storage units, such that, for example, an industrial enterprise can not only optimize its consumption of self-generated PV electricity but also simultaneously shave production-related load peaks.

In addition to the two commercial products, "NRGISE.plan" and "NRGISE.control", "NRGISE.ONE" also includes the "NRGISE.plan" Free open-source software, which provides a freely accessible framework to researchers to develop new control algorithms and system models. This open-source approach makes an important contribution to applied energy research, accelerating research innovations for the energy transformation.

In future, we intend to further develop "NRGISE.ONE" and thus enable its application in the context of a wide range of storage applications and system constellations. Furthermore, we aim to integrate new, sustainable storage technologies, such as those based on sodium or zinc, to support rapid integration into the supply grid.



Schematic representation of the "NRGISE.ONE" product suite: Simulation of the interaction between an energy system and a controller for economic evaluation in a multi-dimensional parameter space.

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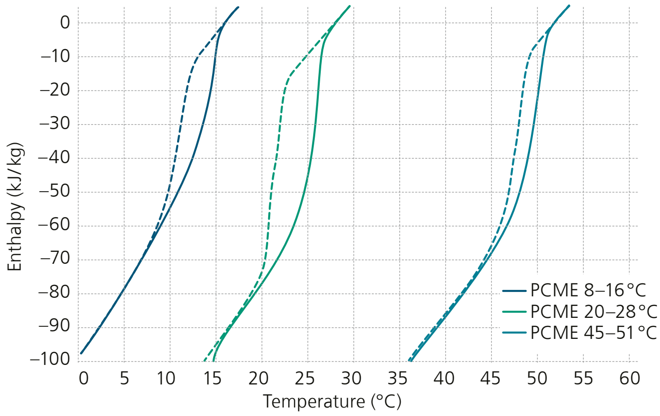
Development of PCM Emulsions as Heat Transfer Fluids with High Heat Capacity

In the "Optimus" project, we are cooperating with industrial partners to develop new emulsions of phase change materials (PCM) and water or water-glycol mixtures for applications in buildings and industry, as well as for heat pump systems and to cool batteries in vehicles. The melting temperature ranges of the applied PCM are from 8 to 16 °C, 20 to 28 °C or 45 to 51 °C. In each case, heat is stored and released again within these narrow temperature ranges.

In our approach, we primarily use paraffins which are dispersed or emulsified in water. The PCM emulsions thus remain liquid, regardless of the phase state of the PCM, and can be used as heat transfer liquids in heating or cooling circuits. At the same time, the components are kept at very homogeneous temperatures even for low volume flow rates, due to the release and absorption of heat during the melting or crystallization processes of the PCM. For industrial clients or building operators, this offers decisive advantages: For example, the volume flow rates in hydraulic circuits can be significantly decreased without reducing the heat transport power or, alternatively, correspondingly more heat can be transported for unchanged volume flow rates.



Enthalpy curves of the PCM emulsions (PCME). Dashed lines – cooling curves; solid lines – heating curves.

Preparation of PCM emulsions in the laboratory.

All of the emulsions that were developed in the project were tested in a realistic hydraulic test circuit with a centrifugal pump, various valves, a membrane expansion tank, and plate heat exchangers, and survived at least 10 000 cycles. We completed up to 100 000 cycles in the experiments. To do so, we initially developed PCM emulsions on the laboratory scale with production amounts of up to five liters and characterized and tested them. In a second step, the prepared compositions were transferred to the pilot production scale and produced in quantities of up to 100 liters. Further upscaling to the cubic meter scale is carried out by our industrial partner, H&R Wax & Specialties GmbH. In this way, also large amounts of PCM emulsions can be produced and are available for demonstration in building or industrial applications.

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

Decarbonizing Industrial Processes: Concepts for Heat Recovery and Heat Pump Applications

The industrial sector is confronted by the task of changing its processes from fossil to renewable energy sources in the coming decades. Thermal processes present a particular challenge. Here, not only the amounts of energy but also the necessary temperature levels play an important role. This applies particularly to heat recovery and the application of heat pumps. In the course of this transition, a methodical approach to integrate processes becomes increasingly important: it addresses the thermal interaction between individual processes. Beyond that, energy-relevant optimization of the individual processes and alternative approaches to supply energy are needed.

There is a need for a consistent, integrated methodology so that targeted decarbonization concepts can be implemented cost-effectively. This applies particularly to the large-scale introduction of new technologies such as industrial heat pumps. The methodology encompasses the following steps:

- data collection
- energy-relevant optimization of the individual processes
- determination of the potential for heat recovery
- concept development to apply heat pumps and thermal storage tanks and
- application of renewable energy to meet remaining energy demands.

Pinch analysis plays an important role in process integration. This analysis allows efficient, economically optimized concepts to be developed for direct heat recovery and the application of heat pumps, as well as the integration of further technologies such as the thermal use of solar energy, combined heat and power (CHP), or thermal storage. Examples from our project work at Fraunhofer ISE show that significant and techno-economically optimized reductions of CO_2 emissions are possible with this method, with comparatively small effort for concept development.

At the Koehler Paper factory located in Kehl, Germany, we applied this approach to reveal opportunities to greatly reduce the consumption of natural gas. In this case, we applied pinch analysis to identify optimization potentials for the complete works, including the paper processing machines and an on-site power plant, and to investigate a potential connection to a local heating network. In addition to optimizing internal heat recovery with heat exchangers, also different concepts for generating steam with heat pumps were developed.

For Adelholzener Alpenquellen GmbH we used pinch analysis to develop a concept that enables the company to avoid energy-related CO_2 emissions in future. In addition to improved direct heat recovery, we also modeled the techno-economically optimal integration of industrial heat pumps. An essential element of the concept is the usage of waste heat from the cooling plant and from wastewater by applying large-scale heat pumps, the optimization of internal heat recovery with heat pumps, and the application of thermal storage.

Our work demonstrates that pinch analysis is suitable to derive measures to reduce CO_2 emissions from heating and cooling in the industrial sector. It supports the development of concepts to apply different technologies for emission reduction, such as heat pumps, thermal use of solar energy, thermal storage, and combined heat and power, and thus allows these technologies to be evaluated and optimized in the industrial context according to techno-economic criteria.

At Fraunhofer ISE, we develop concepts to decarbonize industrial processes.

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Training Test Rig for High-Temperature Heat Pumps with Natural Refrigerants

Around half of the final energy consumption in Germany is due to heating applications (space heating and process heat) in buildings and industry. Much of this energy is still obtained from fossil-fuel sources. One option to decarbonize both industrial process heat up to 200 °C and also district heating is presented by high-temperature heat pumps (HTHP), which can be operated with renewably generated electricity. In order to introduce HTHP successfully, there is a need for efficient cyclic processes and also qualified specialists who can install, operate and maintain the equipment.

We are addressing these challenges in the "KETEC" joint project. In concrete terms we are testing the use of natural refrigerants in HTHP and are developing measures to increase their efficiency.

For this purpose we have planned a functional model of a heat pump at Fraunhofer ISE as a training test rig, which is operated with n-butane (R600), a natural refrigerant. The heat pump can provide heat at temperatures of up to 140 °C and a heating power of up to 40 kW. Commissioning started in June 2024. We have already achieved an operating temperature exceeding 130 °C and temperature rises of up to 100 K. A hydraulic module that was developed at Fraunhofer ISE allows the source and sink temperatures and the volume flow rates to be adjusted flexibly.

A special feature of the heat pump functional model is its construction with many different connection options. These include two compressors, a condenser, a subcooler, an internal heat exchanger, and two evaporators. The working medium, R600, can be compressed in two stages by adding an economizer. We use a simple circuit with four components, such as is frequently applied in cooling technology, as the reference for comparing different circuit configurations. Numerous scientific investigations have demonstrated that the use of an internal heat exchanger is an easily applicable and cost-effective option to increase efficiency. Specifically for large temperature differences between heat source and sink, two-stage compression is advantageous. Depending on the connection circuit, with an open or closed economizer, the hot gas in the first compression stage can be cooled or super-heated further. In general, parallel compression is applied to improve performance. In addition, the working fluid can be stored in and extracted from a separate vessel during operation to visualize malfunction situations such as overfilling or underfilling. The numerous sensors and inspection windows allow changes in state within the cycle to be followed and thus help in understanding also complex circuits and malfunctions.

To complement the training test rig, we are currently preparing a digital learning module that provides basic knowledge on high-temperature heat pumps and preparation for working with the heat pump functional model. In this way, the physical equipment coupled with the digital training module can be applied usefully also in teaching situations.

The KETEC project is funded by the German Federal Ministry of Education and Research (BMBF).

Hydraulic module to set the source and sink temperatures flexibly, ready for transfer to the laboratory.

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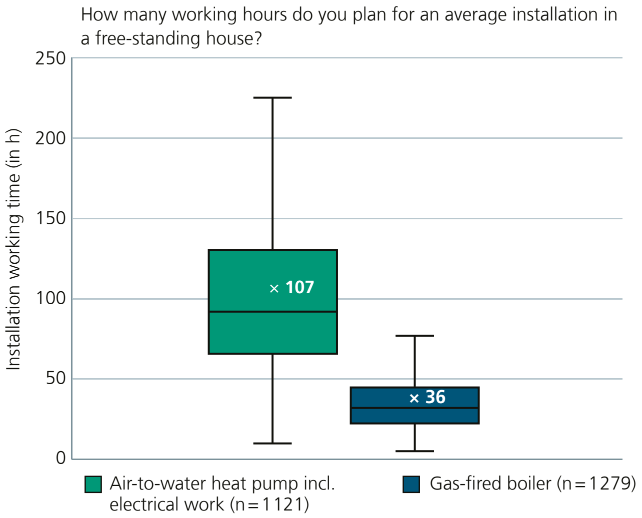
Digitalization for the Heating Trades: Supporting Tradespeople in Implementing the Heating Transformation

Tradespeople are decisive agents of the energy transformation. The plumbing, heating, and air-conditioning trades play a key role in this process. The anticipated future growth in heat pump installation will result in new challenges and tasks for installers in these trades – while there continues to be a scarcity of tradespeople. In order to achieve the necessary increase in productivity, digitalization can support and significantly reduce the load on businesses when documenting the existing situation, planning and preparing materials, and during installation. Continuous access to the same set of data for different applications and process steps is decisive.

In the context of these challenges, we at Fraunhofer ISE are working on digital applications for trades in two research projects. In the BMBF-funded project, "DiBesANSHK", we are developing AI-based image recognition for heating components as well as a generator that can prepare valid hydraulic diagrams based on the information from quotes and the components that have been identified via image recognition. These data are saved in a central system data model and linked to information from publicly accessible sources about the components. Important information for further work on a contract, e.g. for customer service, is thus available at a single source for the trade businesses and allows efficient processes to be followed.

Our research project entitled "WESPE" concentrates on the entire process of fulfilling a contract. We are analyzing the process sequence for many plumbing, heating, and air-conditioning firms, e.g. by interviews, on-site accompaniment, and video analyses, to identify optimization potential. One reason for these efforts is the significantly longer installation time for heat pumps compared to heating boilers, as revealed by surveys showing that heating installation firms plan almost three times as many working hours for installation (see figure). Together with many product manufacturers and wholesalers as industrial partners, we are addressing the topic of digitalization on the basis of data models, with a focus on interfaces, integration, and availability of component data. Within the project, we are developing an augmented-reality tool for image recognition of heating components.

Initial results of our process analysis show that there is potential for improvement primarily at the interfaces between manufacturers and installers, but also within the firms, between the office and the building site. We are thus cooperating closely with manufacturers and installation firms to optimize the information flows at these interfaces and to standardize them. In this way, tradespeople can apply their limited resources in future appropriately to their core business, i.e. the installation and maintenance of systems.



Surveys of more than 1 000 plumbing, heating, and air-conditioning firms revealed longer installation times for heat pumps than for gas-fired boilers.

The DiBesAnSHK project was funded by the German Federal Ministry of Education and Research (BMBF). The WESPE project is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Digital image recognition helps installers during component mounting.

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Heat Pumps with Propane for Buildings – Developing Units to Replace Gas and Oil Heating

Heat pumps and district heating are the most important technologies to decarbonize space-heating units, which are still primarily fossil-fueled. Heat pumps use electricity with a coefficient of performance of three to four to provide heat, making very efficient use of the electricity that is supplied increasingly from regenerative sources.

Ongoing market analyses show: heat pump technology has already become established for new buildings and increasingly for the renovation of free-standing houses. Here, mainly air-water heat pumps that are installed outdoors are being used. The existing building stock, with its restricted space indoors and outdoors, continues to be a challenge. The almost obligatory requirement, introduced by the revision of the F gas regulation, to use natural refrigerants such as efficient, climate-friendly propane requires additional attention.

We at Fraunhofer ISE are addressing these questions with concrete developments for equipment and system concepts in several projects, of which two will be presented here. In the "LCR290" project, we are preparing three exemplary solutions for the current requirements in the existing building stock: heat pump units as a replacement for apartment-based wall-hung gas boilers and, with higher heating capacities, as substitutes for oil and gas heating units in the basement of apartment blocks, as well as for outdoor installation. We are developing these concepts, accompanied by an Advisory Board of 13 heat pump manufacturers and five enterprises from the housing sector, and provide these concepts to our partners for further application.

As a basis for designing the units, we conducted a broad analysis of the existing German housing market with regard to the floor area of typical flats, energy efficiency classes, and heating systems. This indicated that the power classes from 4 to 6 kW for apartment-based heating and 25 to 30 kW for central heating systems are relevant. The test units are being constructed and subjected to the first laboratory measurement campaigns. Initial results show that a capacity of less than 150 g of propane can be easily implemented for wall-mounted units; a maximum of 900 g of propane is planned for the 30-kW units located in the basement. The operating behavior of all three concepts is being analyzed. Suitable safety concepts are being identified and evaluated on the basis of experimental refrigerant release evaluations for different safety scenarios.

Heat pump test unit with a reduced refrigerant capacity and a power of 25 to 30 kW for outdoor installation, developed and constructed at Fraunhofer ISE.

In the "HP-PVT4.0" project, we are developing a system consisting of a heat pump, storage tanks, and PVT collectors. PVT collectors make use of the waste heat of the PV modules and the outdoor air that flows behind them. Thus, they can be used as heat sources for the heat pump. We are paying particular attention to good system integration and control, as well as the use of natural refrigerants. The application of a tank-integrated condenser is being investigated for heating operation. In order to use propane also as a refrigerant, we have identified two approaches requiring small refrigerant capacities, which are currently being measured.

The LCR290 and HP-PVT4.0 projects are funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

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Solutions to Transform District Heating Networks

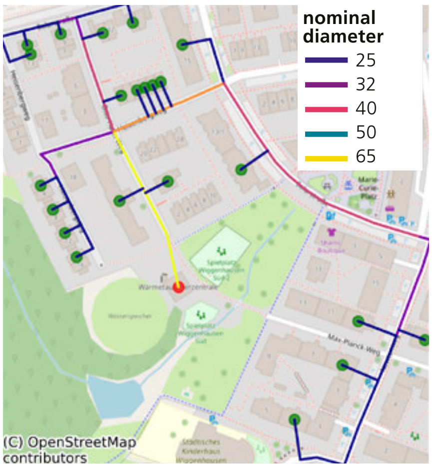
The expansion of district heating networks is an important component for success in the heating transformation. A major advantage of heating networks: To supply energy, they can also use renewable heating sources that are located some distance away from the consumers. Thus, ambient heat from rivers, drains, or geothermal sources can be accessed with the help of heat pumps to provide heat to buildings or industrial plants via the network. Also, if networks already exist to supply energy to residential areas, industrial waste heat sources or heat from solar thermal collectors can contribute, which are often located in the outskirts of cities. Thermal storage tanks complement this system by adapting the fluctuating heat flows to the actual heat demand.

Feasibility studies by Fraunhofer ISE show that the extension of district heating networks is particularly relevant in areas with a high density of consumption that also have close and suitable heat sources. However, as the number of accessed ambient heat sources rises, these networks increasingly contain a large number of distributed heat sources. Compared to many existing networks that include only one central heating plant, the control complexity increases massively. For instance, ambient heat is not always available when needed and is often fed into the network at different temperature levels. Whereas conventional networks can operate with simple control loops, these more complex networks require experienced operators or also intelligent, interconnected control strategies, to enable cost-optimized operation and to guarantee supply security.

To address this problem, we are working in the project entitled "WOpS – Heat flow optimization for sector coupling" on the development of model-based predictive control to achieve optimal disposition planning for the distributed heat generators. To this purpose, a load forecast is prepared from historical consumption data and the input from the individual generators is optimized according to their heat generation costs, taking technical and hydraulic restrictions into account.

In the project entitled "Reallabor Großwärmepumpen" (living lab for large-scale heat pumps), we are addressing another research area relevant to this subject. Whereas small-scale heat pumps for space heating in buildings represent a well-established technology, large-scale systems are not yet widely used, and the planning and authorization process is not yet sufficiently standardized. Within a living lab, we accompany the installation and operation of relevant systems. The goal is particularly to gain experience on operating the systems within a cluster of heating power plants including existing systems, as well as fluctuating source and sink temperatures. The analyses should simultaneously facilitate the complex planning and authorization process for large-scale heat pumps.

Beyond these projects, we are accompanying diverse extension and transformation processes of heating networks, including the planning of the district heating complex in the Upper Rhine region. In the district of Lörrach, the goal is to supply all required heat by using industrial waste heat sources, crossing state and national borders. With our work, we intend to make the complete sequence of planning, authorization, and operation sustainable for the future, so that a CO_2-neutral heat supply in heating networks can be achieved. This should simplify the extension of heating networks and make it feasible to use more renewable heat or waste heat sources.



The Reallabor Großwärmepumpen and WOpS projects were funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

The figure shows an example of a heating network structure that was planned to achieve cost optimization.

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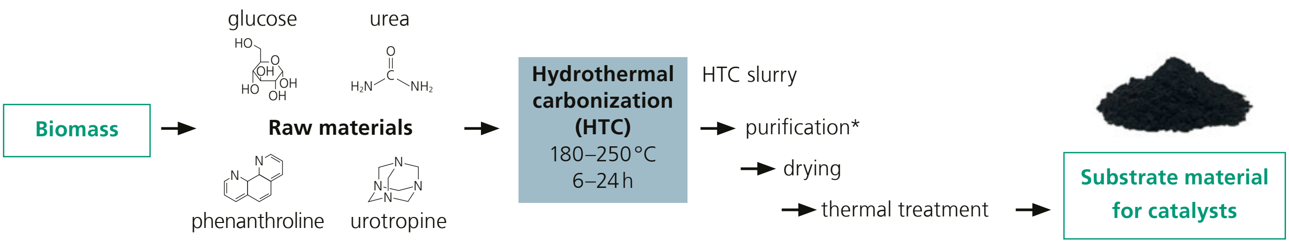
Optimization of Catalytic Hydrogen Generation from Ammonia with Biomass Materials



* After HTC, a purification step in water and ethanol is needed to remove impurities, by-products, and remaining solvents, which can negatively affect the quality, stability, and the foreseen application of the end product.

Schematic representation of the synthesis steps to produce carbon substrate material.

Among other aspects, our future energy system depends on how the transport of hydrogen is organized. Within the TransHyDE lighthouse project, we are cooperating with numerous partners to develop and implement plans for hydrogen infrastructure, globally and within Germany. Ammonia, which is produced from green hydrogen, is considered to be an important hydrogen synthesis product for renewable electricity as harbor and transport infrastructure and a framework of regulations and standards already exist.

The central question addressed in the “AmmoRef” TransHyDE project is how to ensure efficient recovery of pure hydrogen from ammonia. To accelerate the implementation of corresponding facilities, we are cooperating with further research partners to investigate the catalyst as the essential process component. In addition, we are conducting laboratory investigations, to understand the principles of improving efficiency. One focus is the development of new catalysts that do not require noble metals and are stable for a long time. “AmmoRef” aims to optimize both high-pressure and low-pressure processes to recover hydrogen from ammonia and to make them more sustainable.

Fraunhofer ISE is cooperating with the Max Planck Institute for Chemical Energy Conversion (MPI-CEC) to develop non-precious metal catalysts with carbon materials as the substrate, which are produced by hydrothermal carbonization (HTC). During the HTC process, carbon with adapted electronic and structural properties can be synthesized, so that metal species, in combination with the adapted carbon material, operate more effectively than conventional catalysts. Raw materials containing nitrogen from biomass are a particular focus, as nitrogen can influence the reactivity, adsorption properties, electrical conductivity, and surfaces.

Within “AmmoRef”, MPI-CEC provides us with carbon materials based on glucose, urea, phenanthroline, and urotropine, which we impregnate with iron, cobalt, nickel, or a combination of two base metals. Subsequently, the catalyst activity is measured with pure ammonia in a temperature range from 400 to 600 °C. By combining this with material characterization, e. g. X-ray photoelectron spectroscopy (XPS), we can draw conclusions about reaction mechanisms and active catalyst centers. The highest activity is displayed by very inexpensively producible mono-metallic iron catalysts without thermal posttreatment; this confirms the fundamental influence of the substrate material on hydrogen generation from ammonia. The long-term stability and coating properties of carbon materials remain important research fields; we will investigate questions related to coating in the recently started “AmmoCatCoat” project.

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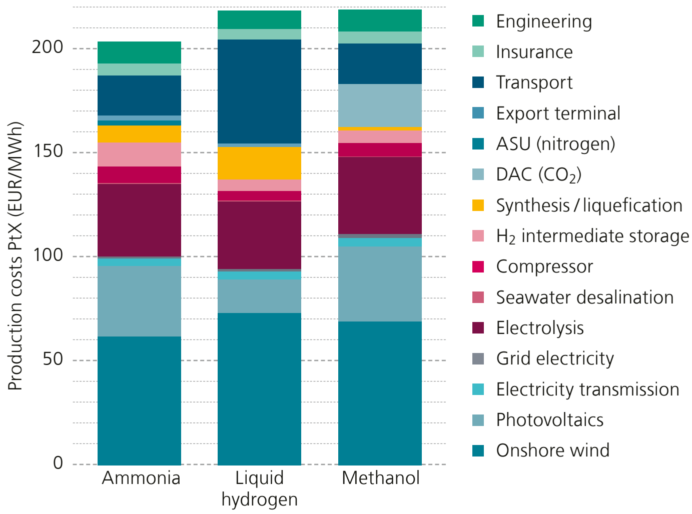
The TransHyDE, AmmoRef, and Ammo-CatCoat projects are funded by the German Federal Ministry of Education and Research (BMBF).

Feasibility Study on Importing Green Hydrogen from Australia via Rotterdam to Germany

Germany depends on the import of renewable fuels such as green hydrogen. Australia assumes a key role as an export country, as the continent features very large available areas accompanied by high average wind speed and solar irradiance levels. Within the tri-national "TrHyHub" project, we have cooperated with the Mid-West Port Authority of Western Australia and the Port of Rotterdam to carry out a comprehensive feasibility study on the export of green hydrogen and derivatives like ammonia. At Fraunhofer ISE, we investigated the complete delivery chain and the associated specific technological solutions for exporting three million tonnes of ammonia annually from Western Australia via the Port of Rotterdam to German customers from 2030 onward.

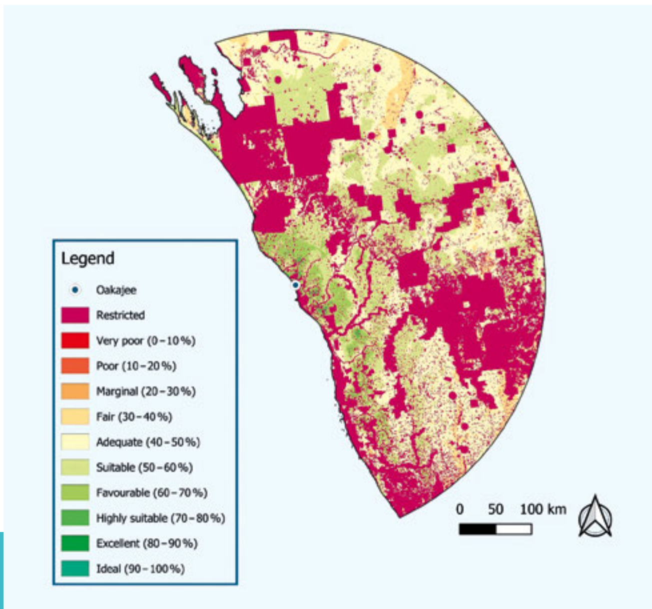
To determine the potentials, we started by applying a high-resolution GIS analysis to identify unsuitable areas for renewable energy conversion and then calculated the remaining theoretical surface area potential. With the help of a multi-criteria decision analysis developed within the project, we identified those areas that are best suited for the installation of wind energy and photovoltaic power plants on the gigawatt scale (figure below). Subsequently, the process chain and transport of the derivatives to the Port of Rotterdam were subjected to detailed techno-economic optimization. To do so, we set up a technical model in the H_2ProSim toolbox (Hydrogen Process Simulation) and determined the cost-optimized component design by applying an optimization algorithm. The variable electricity generation and the limited operating window for the production of hydrogen derivatives were taken into account.

Around 6.9 GW of photovoltaics and 5.5 GW of wind energy, which provide an input power of 4.4 GW for electrolysis, are required at the cost optimum to produce the required amount of ammonia, 3 million tonnes or its energy equivalent. The results show that production of liquid hydrogen, ammonia, and methanol and their transport to Europe would already be achievable in 2030 for energy costs of less than € 225 per MWh (figure above).



Distribution of import costs for different Power-to-X (PtX) fuels in 2030.

The largest share of the total costs in all scenarios is the provision of electricity. Whereas the technology needed for the "ammonia route" is already being applied industrially, further technical developments are still necessary for the production and transport of liquid hydrogen and methanol, applying the Direct Air Capture (DAC) technology to provide CO_2. Our analyses show that the import costs could be almost halved by 2050.



Result of the GIS analysis to determine suitability for onshore wind energy systems in the Oakajee region of Western Australia.

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

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More Efficient Production of Catalyst-Coated Membranes for PEM-Water Electrolysis

In proton exchange membrane (PEM) electrolysis, water is split into hydrogen and oxygen, whereby fluctuat-ing electricity from renewable energy sources can be used. What sounds like a good proposition is shadowed by high production costs: Expensive catalyst materials and the lack of industrialization processes are hindering widespread market penetration. To reduce the production costs and make hydrogen more attractive as a fuel, it is necessary, among other aspects, to improve the treatment processes for the "heart" of the electrolyzer, the catalyst-coated membrane (CCM).

A CCM is produced in four steps:

1. Dispersion of the catalyst inks (catalyst powder, ion-exchange polymer, solvent)
2. Printing the inks to form catalyst layers (< 20 µm thickness) on a transfer substrate
3. Drying
4. Transfer of these layers onto the PEM by hot pressing

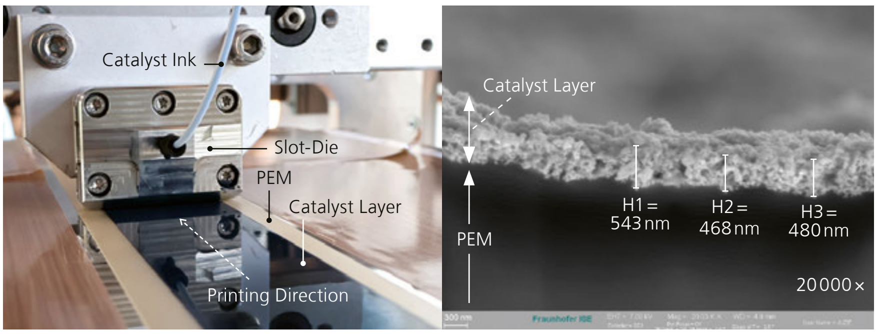
Each step strongly affects the performance of the CCM and must be optimized in detail. Within the "OREO" project, we have established a network of national and international experts on CCM to evaluate a broad spectrum of different industrially relevant CCM production routes. During the project, we compared slot-die coating, screen-printing, spray-coating and doctor-blade printing processes for CCM production and subsequently improved the properties of each of the catalyst inks individually. The results show very similar performances of the generated CCMs, whereby the slot-die coating offers more advantages due to its suitability for continuous roll-to-roll processes.

In addition to the investigation of mass production routes, it is relevant to substantially reduce the required amount of catalyst powder for the CCMs. According to the technical targets for PEM electrolysis published by the US Department of Energy, the total content of noble metals should be reduced in the long term from currently ~1 mg/cm^2 to 0.125 mg/cm^2, and this should be done for an electrolyzer power of 1.6 V at 3 A/cm^2 and 80 °C. This reduction of the noble metal content is accompanied by challenges with regard not only to production technology but also to the lifetime and performance of the CCMs.

Since the beginning of 2024, we at Fraunhofer ISE have been working within the Hyfab3 joint project to establish reference production processes for CCMs with a reduced content of noble metals. These processes should be applicable both for hydrogen generation using PEM electrolysis and also for the related technology with an anionic exchange membrane (AEM electrolysis). The goal is to enable the cell area to be scaled up and to achieve high throughput rates for the anticipated market introduction of CCMs. We have already succeeded in producing electrodes with a thickness of approximately 0.5 µm and a noble metal content of less than 0.1 $mg_{iridium}$/cm^2 . With this result, we were able to exceed the goals formulated by the US Department of Energy (see figure).

In the next development step, we intend to optimize the interface between the CCMs produced by this route and the remaining cell layers. We want to ensure that CCMs with a low content of noble metals can still be contacted well electrically, to ensure that performance is not compromised.

Printing a catalyst layer by applying the slot-die coating process (left); cross-sectional image of a 0.5-µm-thick catalyst layer with a noble metal loading of 0.1 mg/cm^2 (right).



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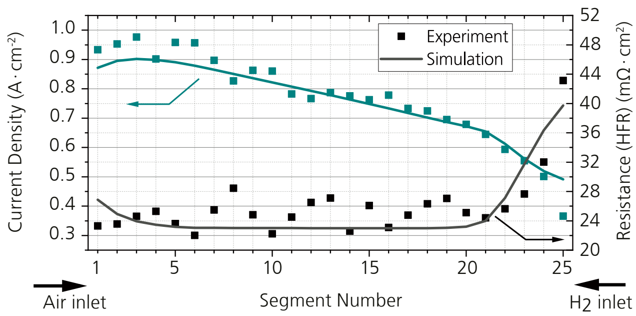
Spatially Resolved Operating Behavior in Automotive Fuel Cells

Operating conditions in vehicles impose high demands on a fuel cell system with regard to dynamics, power density, and lifetime. Our scientific focus here is on investigating inhomogeneous conditions and the specifications on material and operation management that are derived from them.

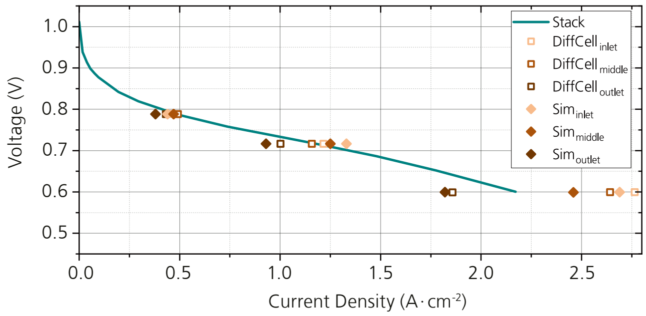
In general, cells with a small area, so-called differential cells, are used for investigations of catalyst-coated membranes (CCMs). Material consumption can be minimized with these cells and constant operating conditions can be set in a well-defined way. In order to transfer these results to the operating behavior of CCMs in an automotive format, real-world operating conditions must be chosen for the characterization as the local conditions within a fuel cell stack differ considerably from the gas inlet to the outlet, both on the cathode and on the anode.

The complex interaction between anode and cathode process-es and the resulting locally inhomogeneous current density make it impossible to estimate the actual local conditions, e. g. partial pressures and temperatures of the gases, based solely on knowledge of the total current and the coolant temperature. To determine the local conditions that really occur within the bipolar plate and to obtain suitable boundary conditions for measurements with the differential cell, we have developed a segmented test cell that represents a portion of an automotive flow field geometry with real channel lengths. We use the data on current density and resistance distribution gained from the measurements to validate a 3D CFD model from our project partner, AVL, within the FC-CAT project.

The upper figure shows good agreement between the measured and simulated current density and impedance distributions over the segmented cell with parallel channels of 25 cm length at a cell voltage of 750 mV. By simulating the coupled processes with this validated CFD model, we determine the local conditions that are then reproduced in differential cells. In this way, we obtain reliable information on the behavior of the membrane electrode unit that is to be investigated in different regions of the active area within the fuel cell stack. The lower figure shows a comparison of the polarization characteristic for the fuel cell stack and the average current density in different regions (cathode inlet, cathode center, cathode outlet) reproduced in the differential cell and simulated with the CFD package from AVL-FireM. The results provide deeper insights into loss mechanisms and provide the basis for optimizing the catalyst layers.



Measured and simulated current density and resistance distribution along the flow channel of a fuel cell.



Comparison of the polarization characteristic of the fuel cell stack and the simulated current density in different regions of the active area using CFD models and measurements of a differential cell.

The FC-CAT project was funded by the German Federal Ministry of Education and Research (BMBF).

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EnStadt:Pfaff – Evolution of a Climate-Neutral Neighborhood

Refurbished administration building in the Pfaff neighborhood, Kaiserslautern.

The energy transformation needs technical, regulatory, and social innovations. These must be established also at the local level and, correspondingly, planning and decision processes must be developed further. Living lab projects offer a valuable research framework to do this. In the "EnStadt:Pfaff" project, we cooperated with seven project partners from academia and industry from 2017 up to the end of 2024 to accompany and research the evolution of the former Pfaff site in Kaiserslautern to become a climate-neutral neighborhood. The neighborhood is located in an inner-city, former industrial area of Kaiserslautern, where previously the traditional Pfaff company had produced sewing machines for 150 years.

EnStadt:Pfaff was conceived as a living lab, in which innovative technologies were developed, demonstrated and tested in practice. EnStadt:Pfaff was based on a holistic evaluation of the neighborhood development with climate neutrality as the overriding goal. In addition to the topics of energy supply and building technology, we have thus also addressed objectives from urban planning, mobility, digitalization, and also quality of life and social participation.

Based on the climate-neutral energy concept, an obligation for solar green roofs was included in the urban development plan. Heat is supplied by a low-temperature district heating network which is fed by the return flow of the municipal district heating network, topped up by waste heat from a chiller. In the energy center, bidirectional charging of electric vehicles is also being tested. Beyond that, we have a mobility concept for a neighborhood with fewer cars, including a business model for alternative forms of mobility, which provides the basis for reducing the prescribed number of car parking spaces per apartment. We developed online platforms, as digital solutions allow efficient planning and operation of climate-neutral neighborhoods.

As part of the renovation of two existing buildings, slim-profile windows, window-integrated ventilation, and façade-integrated colored PV systems were demonstrated. A guideline for the renovation of historic buildings and software for life-cycle analyses were developed. In addition, the planning and decision-making processes for developing the neighborhood were investigated during the project.

The living laboratory center on the Pfaff site, which was developed as part of the project, serves to communicate the results. The individual aspects of the neighborhood development are presented in an exhibition, supported by augmented reality. The results and insights gained from EnStadt:Pfaff were prepared as appropriate for different target groups and made accessible to all actors who are planning and developing the neighborhood, via the website https://pfaffquartier-klimaneutral.de.

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The EnStadt:Pfaff was funded by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Heat Pumps for the Processing Industry: Technological Understanding and Matchmaking

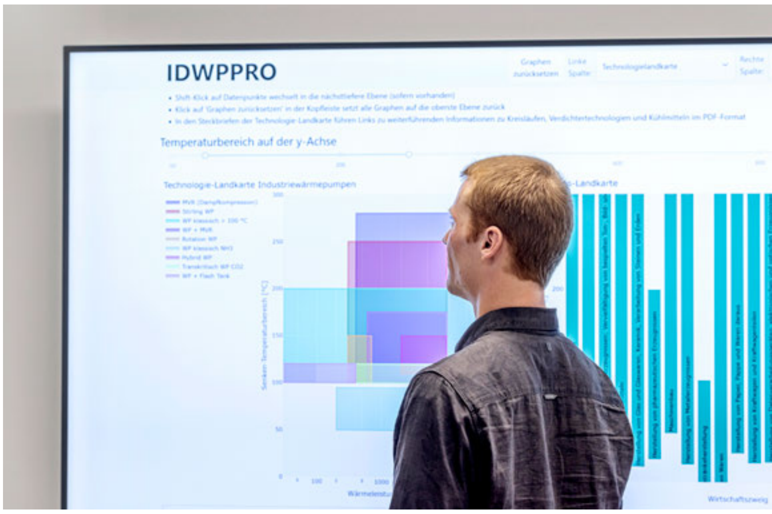
Much of the heat supplied to industrial processes is currently generated using fossil fuels. Heat pumps are an important component for converting the energy system into a CO_2-neutral heat supply. However, providing heat at temperatures exceeding 100 °C is more complex when heat pumps are used instead of combustion processes. Different technological variants are available for this purpose. In the "IdWPPro" project (Identification of industrial heat pumps for process heat), we identified these variants and classified them. Parallel to that, we analyzed different economic sectors to determine the magnitude of the demand for process heat in Germany. Depending on the sector and the process, there are significant differences not only in the amount of heat but also the required temperature level. In processes that require temperatures between 100 and 250 °C, high-temperature heat pumps can be used effectively – this applies to the paper, food-processing, and chemical industries.

In the IdWPPro project, we aim to identify the fundamental properties that distinguish the individual heat pump technologies:

- the underlying thermodynamic cycle
- the compressor technology
- the refrigerant

This classification allows us to quickly match a heat pump technology with the process that is to be supplied with heat. For example, processes that use heat over a wide temperature range can be supplied more efficiently with a heat pump technology that is based on a Joule process.

We have developed an interactive online platform to facilitate the comparison of heat pump technologies and the processes needing heat in various levels of detail. The provided or required heat power as well as the required or provided temperature level are displayed as central parameters.



Within the IdWPPro project, we have developed an interactive technological overview that simultaneously presents the various concepts for industrial heat pumps and the different production processes, so that good matches can be easily identified.

The platform is targeted toward actors from industry, trade, and politics who aim to support the decarbonization of heat supplies, and also toward researchers and manufacturers of heat pumps. The platform offers an overview of commercially available systems, classified according to the operating principle and the temperature and power range. The operating principle of heat pumps is explained clearly on the basis of thermodynamic principles. In addition, we give access to the results of a survey on the relevant industrial processes in Germany and their processing temperatures. In addition to providing information, the platform offers an interactive dashboard that enables heat pumps to be matched with industrial processes.

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

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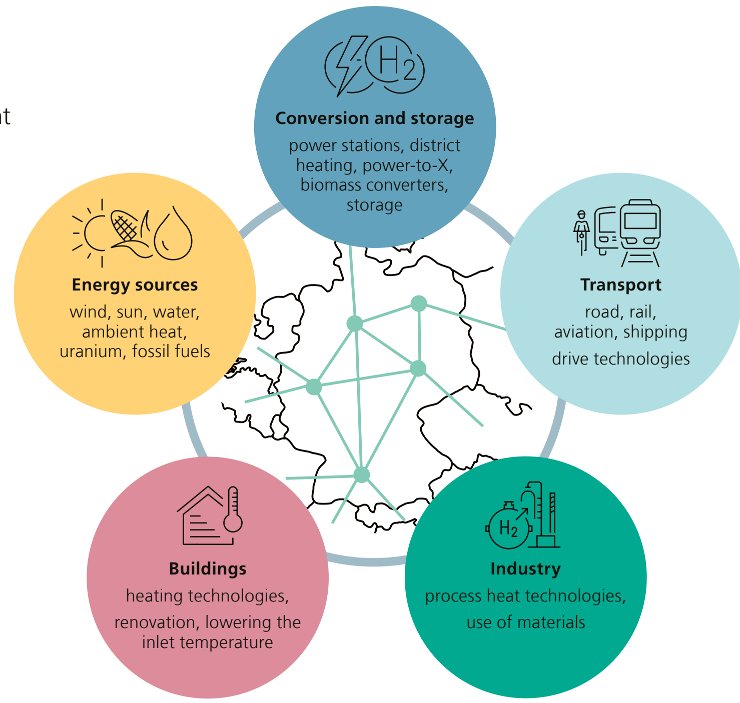
Modeling and Analyzing Transformation and Investments at the Federal State Level

In view of the increasing frequency of extreme weather conditions, climate change is becoming increasingly present in social discourse. The transformation of the German energy system to achieve climate neutrality in 2045 is now in the implementation phase. The study entitled "Paths to a Climate-Neutral Energy System" analyzes the most recent developments in the German energy system and formulates concrete implementation steps for each German federal state. The study addresses developments in the German energy system such as electricity demand forecasting, geopolitical uncertainties, planning of infrastructure, electricity grid expansion, and extension of the main hydrogen grid, and combines these with transformation paths at the level of the individual federal states. For this analysis, we made numerous extensions to the REMod energy system model that has been developed at Fraunhofer ISE. One essential new feature is the regionalization of the model, which makes it feasible to represent transformation paths for ten regions and to consider the electricity and hydrogen grids holistically.

The results of the study show that the demand for electricity is increasing due to electrification and sector coupling, particularly because of electrolysis in the northern German states. We expect greater geographic inequality between energy generation and demand, which brings new challenges for new energy grids. For 2045, the optimization indicates that Lower Saxony, Schleswig-Holstein, and Mecklenburg-Vorpommern will provide one-third of the German primary energy, due to the high wind energy potential in these federal states. In regions with large amounts of wind energy, the establishment of power-to-X technologies will be promoted, whereas the federal states with higher photovoltaic potential will install increasing numbers of stationary battery storage units. To distribute the energy optimally, it is necessary to extend existing electricity transmission capacities and establish an extensive hydrogen infrastructure, whereby particularly north-south and north-west connections will be of vital importance. In addition, the study presents a scenario that addresses growing geopolitical uncertainty, where greater robustness of the energy system to these influences is investigated. The results indicate yet greater significance of efficient conversion and consumption, increasing expansion of renewable energy converters, and still greater electrification.

By further developing our REMod model, we have created the basis for yet more detailed analyses with regard to possible developments in the overall energy systems, in which also questions concerning spatial resolution can be investigated in more detail in the future.

We apply the REMod energy system model to investigate development paths of the German energy system.



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Events in 2025 with Participation of Fraunhofer ISE

January

BAU	Munich, Germany	13. – 17.01.2025
Batterieforum Deutschland	Berlin, Germany	21. – 23.01.2025
SPIE Photonics West	San Francisco, USA	28. – 30.01.2025

February

World Hydrogen MENA	Dubai, United Arab Emirates	04. – 06.02.2025
E-world Energy & Water	Essen, Germany	11. – 13.02.2025
LOPEC	Munich, Germany	26. – 27.02.2025

March

40. PV-Symposium	Bad Staffelstein, Germany	11. – 13.03.2025
PVinMotion	Miyazaki, Japan	12. – 14.03.2025
International Battery Seminar	Orlando, USA	17. – 20.03.2025
ISH	Frankfurt a.M., Germany	17. – 21.03.2025
Volta-X	Stuttgart, Germany	25. – 27.03.2025
Hanover Trade Fair	Hanover, Germany	31.03. – 04.04.2025

April

SiliconPV	Oxford, UK	08. – 11.04.2025
OWPT Conference	Yokohama, Japan	22. – 25.04.2025
CO_2-based Fuels and Chemicals Conference	Cologne, Germany	29. – 30.04.2025

May

Berliner ENERGIETAGE	online	05. – 07.05.2025
PCIM Europe	Nuremberg, Germany	06. – 08.05.2025
Intersolar/ The smarter E Europe	Munich, Germany	07. – 09.05.2025
HOPV25	Rome, Italy	12. – 14.05.2025
tandemPV Workshop	Hasselt, Belgium	13. – 15.05.2025
Symposium Zukunft Wärme	Bad Staffelstein, Germany	20. – 22.05.2025
World Hydrogen Summit & Exhibition	Rotterdam, The Netherlands	20. – 22.05.2025
Berliner ENERGIETAGE	Berlin, Germany	26. – 28.05.2025
EMRS Spring Meeting	Strasbourg, France	26. – 30.05.2025

June

The Battery Show Europe	Stuttgart, Germany	03. – 05.06.2025
SNEC Photovoltaic Power Conference & Exhibition	Shanghai, China	11. – 13.06.2025
LASER World of Photonics	Munich, Germany	24. – 27.06.2025

July

AgriVoltaics	Freiburg, Germany	01. – 03.07.2025

August

ICE International Conference on Electrolysis	Freiburg, Germany	25. – 29.08.2025

September

CISBAT	Lausanne, Switzerland	03. – 05.09.2025
RE+	Las Vegas, USA	08. – 11.09.2025
PSCO	Perugia, Italy	15. – 18.09.2025
EUMETSAT Meteorological Satellite Conference	Lyon, France	15. – 19.09.2025
EU PVSEC	Bilbao, Spain	22. – 26.09.2025
SolarPACES	Almería, Spain	23. – 26.09.2025
European Hydrogen Week	Brussels, Belgium	29.09. – 03.10.2025

October

FVEE Jahrestagung	Berlin, Germany	07. – 08.10.2025
eMove360° Europe	Munich, Germany	14. – 16.10.2025
Hydrogen Technology Expo	Hamburg, Germany	21. – 23.10.2025
European Heat Pump Summit	Nuremberg, Germany	28. – 29.10.2025

November

ISES Solar World Congress	Fortaleza, Brazil	04. – 07.11.2025
Agritechnica	Hanover, Germany	09. – 15.11.2025
Productronica	Munich, Germany	18. – 21.11.2025
DKV Tagung	Magdeburg, Germany	19. – 21.11.2025
12. Solarbranchentag	Stuttgart, Germany	27.11.2025
MRS Fall Meeting & Exhibition	Boston, USA	30.11. – 05.12.2025
IRES International Renewable Energy Storage and Systems	tba	tba

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

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