Introduction

As a result of the growing commitment to renewable energies worldwide, the share of electricity generated from fluctuating sources like solar and wind is steadily increasing. Therefore, new grid-supportive measures are needed to match the demand profile and the availability of supply and thus, to ensure reliable and efficient operation.

Figure 1 shows the power generation in the month of Mai in Germany 2010 and 2018. The dynamic development in terms of increased share of photovoltaics and wind power production can be seen. During this period of time the annual share of renewable energy more than doubled from 19.1% to 40.3%.

In order to achieve the national and international CO2 reduction targets, high penetration rates of renewable energy capacities are mandatory and even more, the coupling of energy consuming sectors is a crucial requisite for a reliable and sustainable energy system. Chemical energy storage based on electricity conversion via water electrolysis to H2 and O2 followed by the conversion of H2 to different energy carriers of interest is a promising option for long term energy storage, clean mobility solutions and a green chemical industry. Furthermore, electrolyzer systems in the distribution grid can be valuable loads for frequency stabilization serve.

The Fraunhofer Institute for Solar Energy Systems ISE with like 1,300 employees is the largest institute for solar research in Europe and has been one of the leading R&D-Service providers in the field of solar energy based energy use for the last 30 years. We are working on creating the technological foundations for supplying energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. With its research focusing on energy conversion, energy efficiency, energy distribution and energy storage, it contributes to the broad application of new technology.
In the division hydrogen technologies, the whole H₂ value chain is being considered. The research activities involve the electrochemical H₂ production, thermochemical H₂ valorization and reforming and pyrolysis technologies and the utilization of H₂ in fuel cells with focus on the mobility sector (figure 2). With that we are tailoring technologies allowing the deployment of the “Matchmaker” H₂ in sustainable energy systems. Integ rally, our research span includes the development of innovative processes to store H₂ in the form of designer molecules fulfilling the criteria of future energy carriers, namely (1) CO₂ “quasi” neutrality (2) sustainability with regard to unlimited availability (3) as low environmental/ecological impact as possible (4) economic efficiency and (5) functionality and best possible integrity with existing technologies.

![Diagram of Sustainable Feedstock, Efficient Catalytic Conversion, and Advanced Products](image)

Fig. 2: Overview of Power-to-X technologies investigated at Fraunhofer ISE

**R&D activities related to clean energy technology**

Fraunhofer ISE develops materials, components, systems and processes in five business areas. In addition to its R&D, the institute offers testing and certification procedures. Furthermore, it features an excellent laboratory infrastructure and is certified according to the quality management standard, DIN EN ISO 9001:2015.

In the business division “Hydrogen Technologies”, R&D services addressing the generation, conversion and further thermo-chemical processing of hydrogen are being under investigation. As part of this division, the department “Chemical Energy Storage”, develops pioneering technologies in the field of electrochemical splitting of water by electrolysis. It is a clean and efficient process to generate hydrogen if the electricity used for splitting the water comes from renewable energy sources. The resulting “green” hydrogen is a universal fuel that can be easily stored and used in many applications. In particular, PEM water electrolysis, which applies a proton exchange membrane (PEM), is well-suited for combination with renewable energy sources. Fraunhofer ISE has been working for more than 25 years on component and system development as well as the integration of PEM electrolyzers in the energy system.

In the department “Thermochemical Processes” the aim is to increase the energy efficiency of thermochemical processes, to reduce CO₂ and exhaust emissions and thus to help the energy transition to success with innovative process engineering solutions. In this context, we are working on the more sustainable production of different fuels and chemicals from different feedstocks (CO₂, syngas, exhaust gas from steel industry, etc.). We also analyse deeply the techno-economic-ecological aspects of the PtX processes.

In the “Fuel Cell Technology” department, we support the development of membrane fuel cell systems for portable, stationary and mobile applications by characterizing single cells, cell stacks and entire systems. Furthermore, we test peripheral and cell components under extreme climatic conditions and with regard to their electrochemical resistance.
Fraunhofer ISE together with the world leading renewable energy institutes AIST and the National Renewable Energy Laboratory NREL (USA) we organize the Gigaton Hydrogen Workshop series. The goal is to identify barriers and pathways to increase hydrogen use from its current level of 60 MMT/yr globally to reach the gigaton scale of hydrogen use (~10x) in the relatively near future in each of our regions of the globe.

**Specific Research activities in hydrogen, CCUS, and related technologies**

The Fraunhofer ISE has been operating a Hydrogen Refueling station since 2012, a hydrogen injection station since 2017 and MW-scale electrolysis test benches since 2018. A Power-to-Methanol mini plant has been designed, built and commissioned in 2017. Also, a scale-down reactor for dynamic methanol synthesis and a pilot reactive distillation unit for OME synthesis are to be commissioned in summer 2019.

In the field of work of Electrolysis and Power-to-Gas we develop standardized measurement procedures for characterizing PEM electrolyzers, evaluate new cell components and stacks for PEM water electrolysis, develop coating strategies for bipolar plates and porous transport layers, investigate degradation mechanisms in PEM electrolysis cells and develop accelerated stress tests, characterize complete prototypes up to the three-digit kW range, perform stationary balancing and dynamic system modeling of electrolyzers and Power to Gas systems to create hydrogen yield prognoses and optimize operating concepts, investigate the grid service capability of electrolyzers, analyze cost structures of different electrolysis technologies, develop business models for the cost-effective implementation of electrolyzers in the energy system, carry out technological and market studies.

**Carbon2Chem (2016 – 2020)**

Together with Max-Planck and the Fraunhofer-Gesellschaft and universities, eight industrial companies are developing a solution that can be used worldwide to convert the exhaust gases from blast furnaces into primary products for fuels, plastics or fertilizers. H2 is a key player to enable the realization of this project goals.

**Power to Methanol (2018-2020)**

CO2 from fermentation processes and hydrogen from electrolysis are used to produce methanol

**NAMOSYN (2019 – 2021):**

This is what the research project NAMOSYN - Sustainable mobility with synthetic fuels is all about. The aim of the project is to develop and test synthetic fuels for diesel and gasoline engines that can be produced and used sustainably.

### 4. International collaboration

- MOU with the University of Cape Town UCT
- LOI with AIST Japan
- Gigaton Hydrogen Workshop series with AIST and NREL
- Power to Liquids and Chemicals workshop 2016 & 2018 & 2020 in Freiburg
- Bilateral Cooperation in P2X development with FREA –AIST: Developing together innovative technologies enabling the deployment of the Power-to-ammonia systems.

**ReactDist (2019 – 2020):**

Fraunhofer ISE innovated OME synthesis process is aiming at a demonstration plant with industrial partners from Germany and Netherlands

Techno-Economic-Evaluation **Power to Ammonia** in Australia: The ammonia production value chain is evaluated in this project on study basis. Coupling 4 simulation platforms, the techno-economics of the stand-alone ammonia production is evaluated.

### 5. Future perspectives

Regarding the expansion of renewable energies in the power sector, Germany has performed very well. However, in future other sectors have to be included as well. Especially it has become clear that’s difficult to reach the agreed CO2 emissions in the mobility sector. In addition the time line is very challenging.
H2 infrastructure in terms of pipelines, refueling stations and storage facilities should be developed for technology deployment. Technology demonstration for H2 production via water electrolysis should be facilitated and measures allowing scaling-up electrolysis technology should be taken. P2X demonstration plants and long time-on-stream operations should be accelerated to have the technologies ready for the rapidly evolving energy transition. Material development for electrolysis, fuel cells and selective P2X catalysts are essential for the development of the modern energy systems components. Sector coupling and smart mechanisms allowing material, data and energy transfer between sectors should be investigated and demonstrated. Barriers against future energy carriers should be reduced and standardization of these products should be facilitated to allow the initiation of new sustainable markets or drop-in new energy carriers in current infrastructures.

Curriculum vitae
Prof. Dr. Christopher Hebling

Personal Details
Prof. Dr. Christopher Hebling
Fraunhofer Institute for Solar Energy Systems, ISE
Heidenhofstr. 2, 79110 Freiburg

Director
Division Energy Technology and Systems,
Business Division Hydrogen Technologies

E-mail: christopher.hebling@ise.fraunhofer.de

Professional Career

Since 05/2019 Honorary Professorship at the University of Cape Town, South Africa
Since 01/2018 Director Division Energy Technologies and Systems at Fraunhofer ISE
(approx. 450 staff, scientists, engineers and students)
Since 04/2011 Director Division Hydrogen Technologies
(approx. 100 staff, 95% external project funds)
01/2001 – 03/2011 Head of department Energy Technologies
10/1999 – 12/2005 Founder and Head of the group ‘Micro Energy Technology’
(Approx. 40 staff)
01/1992 – 10/1999 Scientist in the silicon solar cell department at Fraunhofer ISE

Education

05/2019 Honorary Professorship at the University of Cape Town, South Africa
11/1998 Ph.D. in physics, University Konstanz (“Summa Cum Laude”)  
Publications

Publication of more than 150 journal and conference papers
(Main topics: Integrated Energy Systems, Hydrogen in Sector Coupling, Crystalline Silicon Thin-Film Solar Cells, Micro-energy Technology, Power MEMS, PEM fuel cells, PEM Electrolysis, Power-to-Liquid)
- 5170 citations in total
- h-index = 29 (Jan. 2019)
- www.ise.fraunhofer.de/de/geschaeftsfelder/wasserstofftechnologien.html#conference-paper

Associations/Engagements

- Co-Speaker of the Fraunhofer ‘Hydrogen-Network’
- Board Member of the Fraunhofer Cluster of Excellence ‘Integrated Energy Systems’ (since 2018)
- Advisory Board Member of “f-cell+HFC - Impulse Summit for Hydrogen and Fuel Cells” (2019)
- International Advisory Board Member of the ‘Hydrogen South Africa’ Flagship Program of the Department of Science and Technology DST, Government of South Africa (since 2015)
- Member of the organization committee of the ‘Energy Storage Europe’ conference (since 2014)
- Head of annual Jury meeting for the ‘Green Tech Awards’ (since 2009)
- Member of the advisory board of the ‘f-cell / World of Energy Solutions’ conference (since 2001)
- Venture Advisor - EARLYBIRD Venture Capital (2010-2015)
- Founder and coordinator of the Fraunhofer Future Theme ‘Micro Energy Technology’ (coordinating nine Fraunhofer Institutes) (2003-2007)
- Conference Chair of the:
  - International Workshop 'Perspectives on Power-to-Liquids and Power-to-Chemicals' (2016/18)
  - Intern. Workshop on PEM Electrolysis (2016)
  - Fraunhofer Symposium on Micro Energy Technology (2006, 2007)
  - PowerMEMS 2007
  - TPV6 (Thermophotovoltaic) (2005)
- Participant at the ‘German-American Frontiers of Engineering Symposium’ of the AvH (2008)
- Member of the International Steering Committee ‘PowerMEMS’ Series - ‘International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion (until 2010)
- f-cell Award in bronze (2002)
- Reviewer of national and international project proposals in the field of fuel cell /electrolysis technology, hydrogen model regions, renewable energy systems and energy storage in general.
- Three years education in the field of Gestalt Therapy:
  Degree as a Gestalt Supervisor, Gestalt Therapist, Gestalt Group Leader.

Most cited papers

1. *Photovoltaic Materials, History, Status and Outlook*
   A. Goetzberger, C. Hebling, H.-W. Schock

2. *Visualization of Water Buildup in the Cathode of a Transparent PEM Fuel Cell*
   K. Tüber, D. Pócza, C. Hebling,

3. *Photovoltaic Materials, Past, Present, Future*
   A. Goetzberger, C. Hebling

   A. Hakenjos, H. Münter, U. Wittstadt, C. Hebling

5. *Fuel Cells for Low Power Applications*
   A. Heinzel, C. Hebling, M. Müller, M. Zedda, C. Müller

   A. Schmitz, M. Tranitz, S. Wagner, R. Hahn, C. Hebling

7. *Investigation of Fractal Flow Fields in Portable PEMFC and DMFC*
   K. Tüber, A. Oedegaard, C. Hebling, M. Hermann

8. *Influence of Diffusion Layer Properties on Low Temperature DMFC*
   A. Oedegaard, R. Tunold, C. Hebling, A. Schmitz, S. Moller-Holst

9. *Hydrophilicity and Hydrophobicity Study of Catalyst Layers in Proton Exchange Membrane Fuel Cells*
   H.M. Yu, C. Ziegler, C. Hebling, M. Oszcipok, M. Zobel

10. *A polymer electrolyte Membrane Fuel Cell System for Powering Portable Computers*
    K. Tüber, M. Zobel, H. Schmidt, C. Hebling