2019/2020

Munich School of Engineering

Annual Report

2019/2020

Munich School of Engineering
Annual Report

Contents

Andreas Battenberg / TUM

President’s Preface

Thomas F. Hofmann
President

As a university of excellence, the Technical University of Munich aims to play a pioneering role in the area of sustainability. We are convinced that, especially for a technical university, sustainability and excellence are not mutually exclusive; on the contrary, they are mutually dependent. When we create new technologies, the results must also meet the best standards in ecological, social and economic terms. Therefore, we must utilize these changing times because the challenges ahead of us call for immediate and resolute action.

We have made sustainability a strategic priority of TUM in all its mission agendas. Beyond expanding our wide range of research and teaching activities in climate research, clean energy, smart mobility or prevention and health, we introduced the TUM Sustainability Office to implement an institutional strategy to lower CO_2 footprint and energy consumption and increase resource awareness across the entire university. In just one year, we have achieved great progress, despite the pandemic.

Researchers of the Munich School of Engineering (MSE) and related chairs have developed a roadmap to reduce greenhouse gas emissions and subsequently future-proof our Garching campus. The MSE will take on a vital role in orchestrating the energy transformation and will combine the emission reduction efforts with novel mobility concepts.
As a result, our biggest campus will become a vibrant case study for others to follow.

The MSE, as an integrative research center, already provides a platform for highly relevant networks of energy research. To bolster our portfolio, TUM will expand the school’s proficiencies to material and process engineering, since new materials and production methods will provide the necessary conversion hardware for the renewable energy systems of the future. Similarly, process engineering will remake practices such as vertical farming into energy sufficient and reliable industries.

As one of Europe’s leading universities, we have the knowledge, the scientific manpower as well as the necessary infrastructure to not just be a part of the sustainability revolution, but rather take on a leading position. We are capable of analyzing framework conditions, processes and requirements for a sustainable society, and are therefore able to provide recommendations for political and corporate action.

The swift movements of the modern world have placed great challenges upon us. However, if we succeed in establishing TUM as integral leaders and catalysts for sustainable development and innovation, our scientific findings and their application will make decisive contributions for the good of society.

Prof. Dr. Thomas F. Hofmann, President

Director’s Message

Thomas Hamacher
Director

There is hardly any doubt that the reduction of and the subsequent complete elimination of greenhouse gas emissions is the biggest challenge in the coming decades. Within this challenge, the transformation of the energy system is a key element.

The debate about the best pathways and measures is on fire. Still simple and clear approaches are rare. A hydrogen economy is rather different from an all electric world and self-sufficiency requires a complete different system than a new global energy trade. A central mistake of most debates is to mistake sheer quantities for reliable indicators: The reduction in greenhouse gas emissions coupled with economy indicators like economic profitability and life expectancy are the central elements, not the number of electric cars on the street and/or the PV panels on the roofs. A major shift in the regulatory paradigm away from micro managements is more than necessary.

I like to exemplify this challenge with two examples, which came across the work of MSE:

The master plan for geothermal heat sounds rational and feasible, but it requires a central institution to plan and construct these hundreds of boreholes and the new transport infrastructure (more information found on p. 11). Instead of doing this in a state-directed fashion, a new approach is necessary, which keeps the grand idea in mind but develops step by step a system still competing with other technologies into an open and fair fashion. The structure could be divided into independent heat suppliers, a transport company and many customers at various power levels – similarly to the electri-city grid as the essential infrastructure. This just demonstrates that the transformation can only happen when technological innovation goes hand in hand with economic and orga-nizational innovations. TUM and MSE are the nucleus to organize and initiate these kinds of projects. A new courage is necessary in order to take responsibility for a changing world.

The second example is the coal power plant Tuzla 7. Chinese investors finance this project in Tuzla, Bosnia. The power plant would manifest the coal technology at this site for many decades to come and stays in stark contrast to the European goal to decarbonize the economy. The experience in coal technology and the need for power in the growing Bosnian economy reveals the dilemma between environmental and economic concerns. This obviously requires new approaches. A solution, which sustains the economic growth while not compromising climate change, is on demand but not at hand. Today TUM hosts many brilliant students and employees from Bosnia and many other countries in the world. We have to learn to include them in a much broader debate about the future of energy and climate. A purist self-centered debate is sure to fail. The opportunities to become a real international university were never better than today. Still it requires a new openness.

If we succeed to combine all loose ends around climate and energy at our university, we can become an important and strong voice in the debate. A lot of work lies ahead of us.

Preamble, Dean of Studies

Prof. Phaedon-Stelios Koutsourelakis,
Dean of Studies MSE

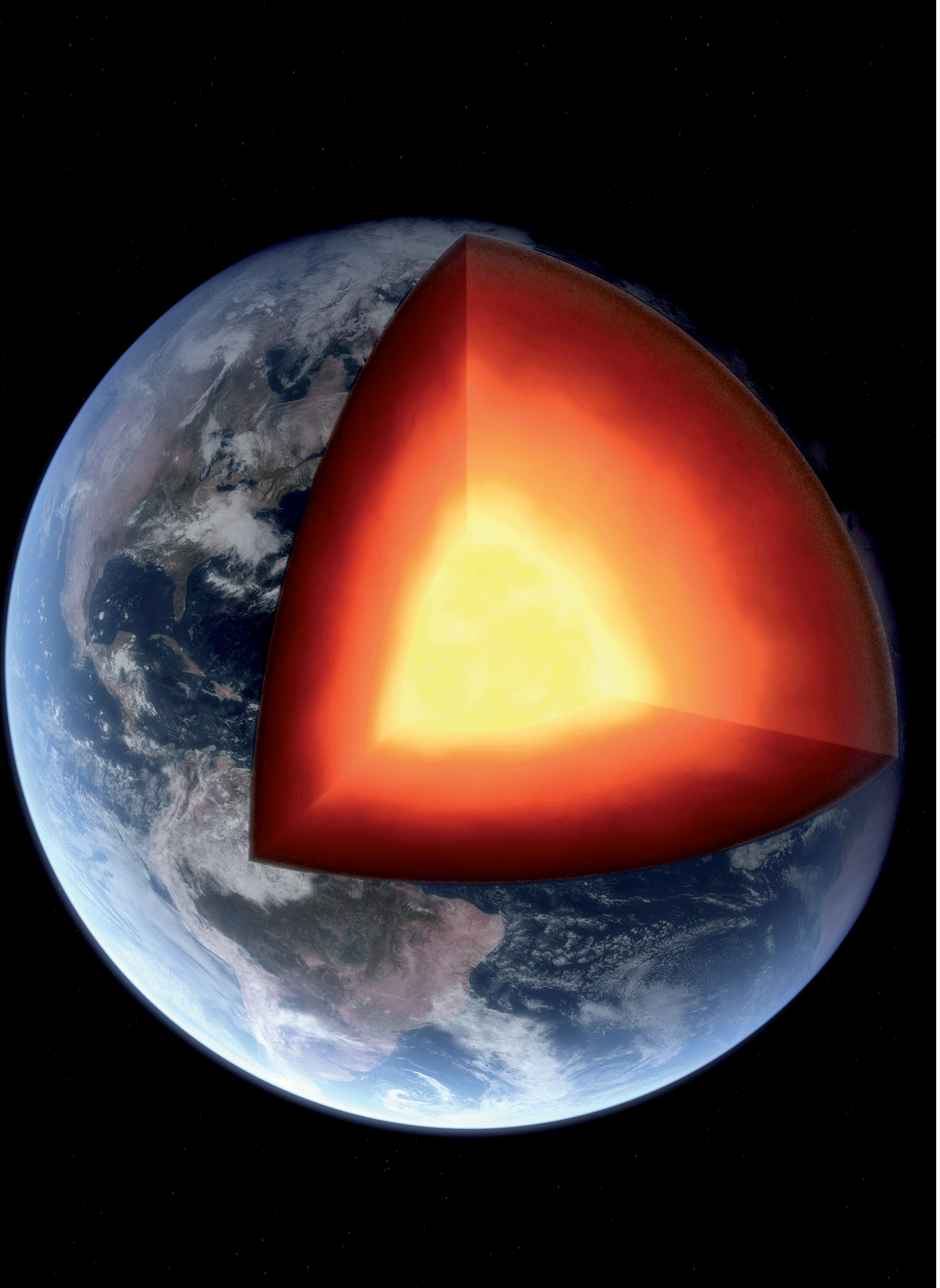
Since its inception in 2010, the Munich School of Engineering (MSE) has sought to enhance TUM’s teaching portfolio by offering interdisciplinary programs that amalgamate current trends on university-level, in engineering education and to provide students the requisite foundation in order to thrive in the rapidly changing industrial and technological environment.

While no one can predict future developments with certainty, it is widely accepted that engineers of the future should be capable of synthesizing knowledge and problem-solving skills from different (not only engineering) disciplines, should be prepared to compete at an international level, must quickly adapt to new trends and be adept at acquiring new skills when necessary. This unavoidably raises the question: how can one be educated to work in, or even lead a sector that perhaps does not even exist today?

In the Bachelor’s Program, “Engineering Sciences” (BES), we believe that the best way to achieve this is by building the strongest possible foundation that is not rooted in a particular discipline. We believe in exposing students to many different perspectives, challenging their ability to synthesize and be creative. The program consists of an intensive syllabus (210 ECTS), which exposes students to topics from all engineering disciplines, natural sciences, life sciences as well as informatics. It introduces students to engineering research as well as industrial practices and enables them to build a strong, interdisciplinary foundation that will allow them to work in many different industrial sectors or to directly transition to a very wide range of M.Sc. Programs.

The goal of building a strong, interdisciplinary foundation permeates the three master’s programs currently offered by the MSE. The M.Sc. program in “Industrial Biotechnology” prepares its students to meet challenges in bioprocesses and biomaterials. The M.Sc. program in “Ergonomics – Human Factors Engineering” enables students with different backgrounds (e.g. from engineering, psychology, design or sports) to analyze and design human-machine interfaces in various engineering contexts. Finally, the M.Sc. Program in “Materials Science & Engineering” provides an interdisciplinary perspective on materials science with particular emphasis on mathematical and numerical modeling as well as materials in the context of various engineering systems.

The COVID19-pandemic forced us to redefine our means of instruction, our ways of interacting with students and the university experience as a whole. As with every challenge though, comes an opportunity. In this regard, we have had the chance to re-evaluate our teaching strategies, to develop new tools and ways of reaching out to students. While there is no substitute for direct, personal contact, faculty and students have shown tremendous adaptability and were quick to adjust to the new conditions. The digital teaching material that has been developed over the last year as well as the arsenal of tools that by now have been strongly integrated, will continue to be used and will ultimately enhance the teaching formats at the MSE even when normalcy has returned.



iStock.com\fpm

Research Highlight

Master Plan Geothermal Energy Bavaria

Assigned by the Bavarian Ministry of Economic Affairs, Regional Development and Energy, the GAB developed a master plan for Bavaria in 2020 (Keim et al. 2020). This master plan shows the enormous deep geothermal energy potential and how it could be optimally utilized and strategically as well as continuous expanded until the year 2050. The demand for space heating and hot water estimated in this study amounts to almost 160 TWh (p. 98, Fig. 5).

A total of almost 100 district heating demand areas in Bavaria were identified where district heating is a potential supply technology. The discovery of further geothermal wells is a fundamental prerequisite for the economic success of deep geothermal energy. This can be predicted comparatively well for the Molasse Basin. According to the estimates, the deep geothermal potential in the Molasse Basin is capable of supplying 80% of the district heating demand with an installed capacity of 7,655 MW_{th}. However, there are significant local differences in terms of predictability. Regarding geothermal sources, the prediction is comparatively good, especially in the greater area of Munich and in the East Molasse Basin, evidenced by the successful operation of numerous geothermal plants.

Furthermore, in many parts of the Molasse Basin, particularly favorable geothermal conditions exist, but they do not directly coincide with heat consumers above ground. In these cases, there is the possibility of using interconnected pipelines to transport the heat to the consumers, thus optimally exploiting the potential. Since geothermal energy has its strength particularly in the base load supply, the prerequisite for the economical operation of a plant is the sufficient demand of heat distributed a district heating network. According to the results, district heating interconnectors are considered to be the key element for the expansion, enabling an increase in the utilization of the plants. This has the effect of increasing economics and thus offering the opportunity to save large amounts of CO_2 in the heat supply.

To cover the base-load heat supply in the identified areas, about 90 geothermal doublets and 120 km of interconnected pipelines would be necessary - this would save almost 2 million tons of CO_2 emissions per year.

Andreas Battenberg / TUM

Students

Studying at MSE

The demand for scientists able to co-operate beyond the borders of their traditional scientific disciplines is steadily growing. Therefore, the Munich School of Engineering (MSE) was founded in 2010 in order to concentrate scientific activities and competences in both research and teaching on interdisciplinarity. MSE is institutionalized as an Integrative Research Center with doctorate-granting rights.

In the field of teaching, MSE offers research-orientated study programs that focus on engineering sciences with a specific interdisciplinary approach. Our programs offer mathematically-gifted and scientifically-inclined students the opportunity to examine results of fundamental research and the entrepreneurial viability of new technologies. This opens up exciting professional opportunities in the interdisciplinary fields of the future.

Since Winter Semester 2010/11, the Munich School of Engineering offers the bachelor's program Engineering Science and the master's program Industrial Biotechnology. In Summer Semester 2014, the orientation program studium MINT was established, followed by the master's program Ergonomics – Human Factors Engineering in Winter Semester 2014/15. Finally, the newly developed master's program Materials Science and Engineering was launched in Winter Semester 2017/18. Professors and lecturers from twelve TUM departments contribute to all of these study programs, thus representing a wide range of subjects and scientific perspectives.

The Engineering Science program provides broad method-based and fundamental scientific training in the first two years, with primary focus on mechanics, mathematics and the natural sciences. In the last year, students can create their own individual curricula to prepare for and orientate towards their prospective master's courses.

The Industrial Biotechnology program qualifies graduates from different bachelor's programs in science and engineering for the interdisciplinary field of industrial biotechnology. Subjects taught include biotechnology, food science, process engineering, chemistry, physics, agricultural science, robotics and information technology.

The Human Factors Engineering program trains students in the creation, implementation, and evaluation of human/technology interaction, according to future needs in various fields of application. Students acquire the ability to design, evaluate and enhance human-machine-interfaces in different technical domains.

The new program Materials Science and Engineering addresses the current and prospective need for scientifically oriented interdisciplinary education in materials science and engineering. The focus is on multiscale materials sciences, materials in engineering applications, mathematical modeling and quantification of uncertainties. The program qualifies graduates in particular for research and development in interdisciplinary branches of industry.

Beyond this, studium MINT offers insight into various bachelor's programs at TUM in order to allow participants to find out more about their personal interests and strengths before enrolling in a certain program.

Bachelor's Program Engineering Science

Since its initiation in 2010, the bachelor's program Engineering Science (B.Sc. ES) has established itself as an innovative, theoretically-oriented course of studies and an attractive alternative to classical academic engineering programs. The program's target group is talented individuals who express interest in both mathematics and natural science subjects and do not yet want to choose their specialisation regarding their academic and professional careers being in the bachelor's program. The B.Sc. ES provides students with a first-class scientific education in the classical engineering subjects as well as the opportunity to acquire a differentiated discipline-specific specialization, ranging from the natural sciences and mathematics to informatics.

Our graduates are therefore perfectly equipped to solve complex problems across the entire range of the engineering sciences and its interfaces with the natural sciences. It is exactly at these interfaces where solutions to society's future big challenges need to be found. The B.Sc. ES is committed to providing today's students with the know-how to face these challenges of tomorrow.

Coordination:
Olga Marini
Daniel Hartenstein (until 2019)

info.engineering@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52705
www.engineering.mse.tum.de

Intention and Focus

The B.Sc. ES prepares students for a steadily increasing diverse range of career options and answers the need for prospective junior engineers to have firm interdisciplinary knowledge beyond classical engineering. Thus, the program is thoroughly interdisciplinary and strongly research-oriented with a focus on mathematics, natural sciences and life sciences. Consistently bilingual (approx. 50% German and 50% English), this intensive study program comprises 210 ECTS points instead of the usual 180 points and presents a challenging yet intellectually stimulating and personally rewarding experience for its students.

Admission and Entrance requirements

Applicants' qualification for the program is evaluated by an aptitude assessment procedure. A higher education entrance qualification, obtained in Germany or abroad, and above-average interest in mathematics, natural sciences and engineering are assessed as follows:

- primary consideration of final school-examination grades
- special consideration of grades in mathematics, physics, chemistry, informatics, German and English
- Consideration of additional qualifications

In cases where this procedure does not yield entirely clear results, applicants are invited to a 20-minute interview conducted by two lecturers of MSE to finally assess the applicants' suitability for the study program. The aim of the interview is to test applicants' aptitude in mathematics and science subjects, in problem-solving and logical thinking, and their English language skills.

Fachschaft MSE / Pauline Haver

Our freshers at the Semestereinführungstag 2019

As a distinctive feature of the B.Sc. ES, students have the opportunity to take a research internship (duration: four months) either at one of TUM's many research groups or at an external research facility, both national and international. The research internships offer students the possibility of gaining first-hand experience in cutting-edge research at a very early stage in their academic careers.

In their final year, students can choose from a multitude of different TUM courses to create their own individual curriculum of studies, thereby orientating themselves towards a particular professional field. In addition, students acquire an individual profile and necessary expertise that qualifies them for a subsequent master's program – either in conventional engineering fields or in the applied sciences - at TUM or at other universities, both national and international.

Owing to the program's interdisciplinarity, students have a wide array of academic fields to choose from in finding a topic for their bachelor's thesis: the full range of sub-disciplines of engineering science, as well as numerous areas in the applied natural sciences.

As an essential feature of the B.Sc ES program, graduates have the opportunity to continue their studies at TUM in pursuing an interdisciplinary or a conventional master's program in various departments. Depending on their individual specialization, over 40 different TUM master's programs are open to them.

TUM departments involved in B.Sc. ES teaching

- Chemistry
- Civil, Geo and Environmental Engineering
- Electrical and Computer Engineering
- Informatics
- Mathematics
- Munich Center for Technology in Society
- Mechanical Engineering
- Physics
- TUM School of Life Sciences Weihenstephan

Recurrent Events:

- „Semestereinführungstag", Welcome event for all new B.Sc. ES students and general introduction to main issues and important facts of the study program
- Welcome event for international students
- Information event "Studies Abroad"
- Information event "Individual Focus and Orientation in the B.Sc. ES"
- Information event "Bachelor's Thesis and Graduation"
- "Tag der MSE", Farewell ceremony for all graduates and awards for the best graduate(s)

Support during the studies:

- Mentoring by a professor
- Peer mentoring
- Peer mentoring for first-year students

Fachschaft MSE

Graduates of the B.Sc. ES at the Tag der MSE 2019

Master’s Program Human Factors Engineering

Coordination:

Dr. Christiane Hamacher
info.hfe@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52706

www.hfe.mse.tum.de

Modern technical products and processes feature a number of desired attributes: easy and convenient in use, and efficiently supporting their users while not causing any lasting detrimental effects for people. The trend towards even greater functionality and power density in technical products and processes makes this increasingly difficult to realize. Society and individuals today have ever-growing demands with respect to comfort, safety and health aspects of the technology they use.

It is clear that no scientific discipline alone can deal with this complex interplay of seemingly opposing requirements. Therefore, knowledge and insight from science, engineering and the humanities need to converge.

MSE overcomes this challenge by offering the interdisciplinary master’s program Ergonomics – Human Factors Engineering (HFE), which qualifies students for a transition to a doctoral program, or for careers in industry within the field of human factors or human-centered engineering.

After graduation, HFE graduates are specialists in the design, implementation and evaluation of future concepts for man-machine interaction in automotive, aerospace, sports equipment, production and software industries. They have the ability to employ a range of interaction principles and technologies to achieve specific ends, to configure exactly the right automation levels, and to plan, execute and analyze the associated hypothesis-driven usability and controllability tests. They are educated to address ethical questions concerning the introduction of technical products and processes.

This master’s program is the result of the close co-operation between the following departments: Architecture, Mechanical Engineering, Electrical and Computer Engineering, Informatics as well as Sport and Health Sciences.

HFE attracts an increasing number of students from TUM as well as from external universities both in Germany and abroad. There are currently 140 students registered in the program.

In this research field, graduates serve as experts to take the above-mentioned development and testing methods to the next level and to address research topics on man-machine interaction across technical domains (e.g. co-operative adaptive systems in production mobility). Our training provides the skills to put together and to coordinate interdisciplinary research teams for creating an efficient and productive working climate.

Human factors engineering: Research assisted by virtual reality Sebastian Mast / TUM

This includes activities in the following areas:

- Design and evaluation of technical products, consumer goods, software and websites
- Interaction design for mobile devices and information and communication media
- Security management in organizations with the potential for high risk
- Research and development in the field of human-machine interaction and ergonomics

Profile of the study program

The master’s program HFE is taught predominantly in German and is aimed at graduates with a good academic record from a bachelor’s program in humanities or engineering, such as mechanical engineering, electrical engineering, computer science, sports science, psychology, architecture, design, or a comparable bachelor’s program.

It is a full-time program that comprises of 120 ECTS points spread over 4 semesters. In the first two semesters, lectures concentrate on topics related to human factors engineering. The program continues with an interdisciplinary research project and ends with the master’s thesis.

Master's Program Materials Science and Engineering

Coordination:

Dr. Christiane Hamacher
info.matscieng@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52706

www.mse.tum.de/materials

Technological developments show an increasing mutual perfusion of the natural/life sciences and engineering. Thus, modern education in engineering is faced with the challenge of respecting classical disciplines while also including and representing interdisciplinary aspects. The special knowledge of the material properties, their characterization and description by means of mathematical models, as well as monitoring and assessment, is key in all engineering disciplines. Research and development of novel materials and the design of interconnected systems are essential and equally permeate all areas of technology.

The need for scientifically oriented interdisciplinary education in materials science and engineering has emerged over the last decade. The master's program Materials Science and Engineering (M.Sc. MS&E) addresses an area of great significance for both the economic and research environment in Germany, and particularly in Bavaria. It connects to the successful bachelor's program Engineering Science or similar programs, but with an added focus on materials science and a strong emphasis on research. Graduates from university education programs in engineering with a specific interest in mathematical modelling have the chance to extend their education both in materials and engineering sciences.

The primary emphasis lies on the physical and mathematical modeling of complex technical and physical systems. The term "modeling" here refers to the penetration of systems by basic engineering disciplines and to the ability to make predictions based on numerical calculations and simulation methods. "Prediction" is no longer restricted to the purely deterministic description of the expected system state, but also includes uncertainty prediction (uncertainty quantification). The shift of paradigm in engineering sciences towards predictive simulations (e.g. prediction by simulation with a quantitative statement about prediction reliability) must be reflected in engineering education. Consequently, basic probability theory, probabilistic considerations and methods in the various disciplines are a focus in teaching. The curricula involves physics, chemistry, mathematics, computer science, life sciences and all engineering departments at TUM to tackle the importance of interdisciplinarity. This supplies the opportunity to deepen education in materials research without neglecting the fundamental engineering sciences. Furthermore, the Advanced Research Internship, characterized by close mentoring and supervision in customized courses to foster scientific reading and writing, presents an important component of this program.

Master's Program Industrial Biotechnology

Industrial Biotechnology ("white biotechnology") involves the use of microorganisms or enzymes to create industrial products, such as specialty and fine chemicals, foodstuffs and food additives, agricultural and pharmaceutical intermediate products and process materials for the manufacturing industry. Over the last few years, the production of bulk chemical products and fuels has also increased. The demand for specialists in the field of industrial biotechnology with a broad range of expert knowledge in bioscience and process engineering to work across a number of disciplines is continually increasing. MSE meets this increased demand by offering the interdisciplinary master's program Industrial Biotechnology (IBT). IBT first started in the winter semester 2010/2011 and attracts an increasing number of students from TUM as well as from external universities, both domestic and foreign. There are currently 100 students registered in the program.

Coordination:

Dr. Christiane Hamacher
info.biotech@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52706

www.biotech.mse.tum.de

Study program profile

IBT aims at graduates with a bachelor's degree in science or engineering, as both bioscience and process engineering methods are equally important in exploiting the technological and industrial potential of new biocatalysts, and in implementing new biological production processes on an industrial scale. Therefore, interdisciplinary fundamentals, based on a specially tailored curriculum, are taught in the first two semesters to prepare students for their future working environment. Choosing from a list of required elective modules, students and mentor put together an individual curriculum that has been adapted to the bachelor's degree:

- Bioscience fundamentals: Students with a bachelor's degree in engineering gain an understanding of bioscience fundamentals.
- Process engineering fundamentals: Students with a bachelor's degree in bioscience learn the fundamentals of process engineering.

After understanding the interdisciplinary fundamentals, students receive specialized training in the following four key areas during the second and third semester:

- Enzyme engineering: Design of biocatalysts for industrial biotechnology
- Metabolic engineering: Analysis and design of metabolic networks in microorganisms
- Bioprocess engineering: Bioreactor and bioprocess design to achieve efficient production processes with optimized biocatalysts on an industrial scale
- Bioseparation engineering: Design of isolation and purification processes for the efficient supply of bioproducts with required purity on an industrial scale

Students can then choose a fourth field of specialization, having the opportunity to select courses at TUM or at a different university.

Students complete their master's thesis in the fourth semester. This independent academic work is based on a topic of relevance to industrial biotechnology and is supervised by a professor or any expert supervisor of TUM who is involved in the study program.

The standard duration of the program is four semesters. The courses are offered by the mechanical engineering and chemistry departments, the Weihenstephan Science Center and the TUM Campus Straubing for Biotechnology and Sustainability. The language of instruction is German, with a few selected courses offered in English.

After graduation, the students consider themselves very well prepared to work in both biotechnology as well as engineering with excellent job opportunities in research and industry. The number of applicants and students is steadily growing since its inception in 2010. The study program qualifies graduates for a transition to a Ph.D., for example at the TUM Research Center for White Biotechnology, or alternatively for challenging careers in the area of industrial biotechnology.

Research practice

The TUM Research Center for White Biotechnology is a strong, interdisciplinary research and training unit. For students in the master's program Industrial Biotechnology, a practical research component at this center is obligatory and is one of the highlights of the program. The technical facilities for research, teaching and technology transfer at the TUM Research Center for White Biotechnology include a screening lab in Weihenstephan and a pilot plant for industrial biotechnology in Garching. The plant is unique in its international academic landscape, offering researchers access to new biocatalysts and bio-products as well as providing students with practical training in the field. Fermenters with a capacity of up to 1.000 liters and the requisite facilities for the isolation and purification of products allow researchers to examine how processes can be scaled up from laboratory to pilot scale.

studium MINT

The TUM Orientation Semester for Mathematics, Engineering, Computer and Natural Sciences

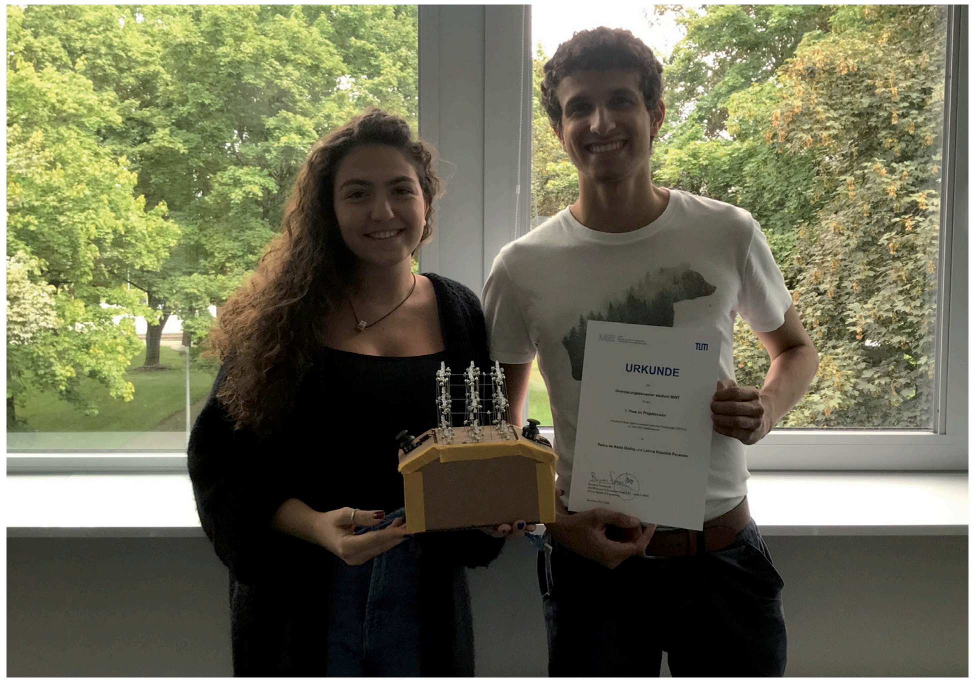
The primary goal of studium MINT is to establish a reliable foundation of basic scientific and technical knowledge within one semester. By getting to know all Science, Technology, Engineering and Mathematics (STEM) disciplines, students are enabled to choose a bachelor's program that fits their individual interests and strengths. Studium MINT not only supports them in taking the right decision regarding their prospective undergraduate program, they also get a solid preparation in basic STEM foundations like mathematics and physics. The interdisciplinary hands-on project brings broad engineering fields together. Students plan and realize their own prototype by programming a microcontroller, installing electronic elements as well as casing and designing the final product with additive and cutting manufacturing. Prizes are awarded to the three best teams. In 2020, two students have been rewarded with 1st place building an LED cube with lots of features and being able to play Tic Tac Toe game against each other.

Coordination:

M.Sc. Benjamin Farnbacher
info.studiummint@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 16094

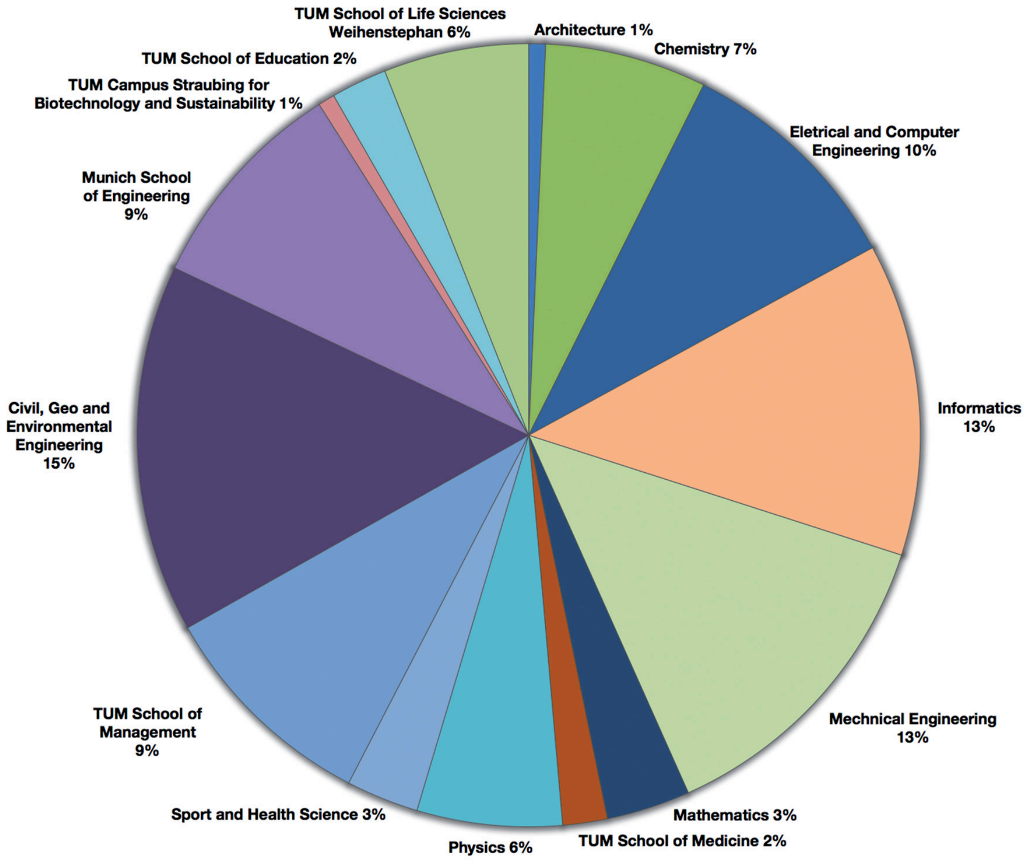
Farnbacher / TUM



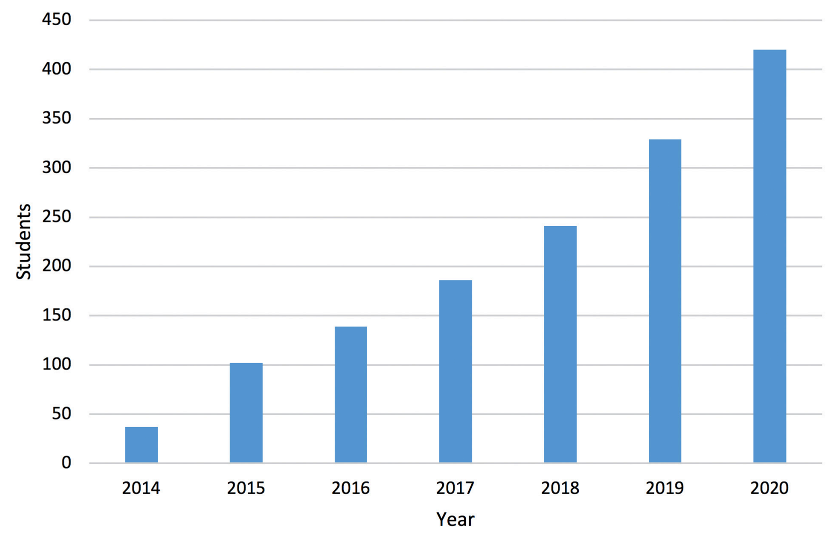
The winning duo of the interdisciplinary hands-on project with the LED Cube

Institutions involved in studium MINT teaching

- Chemistry
- Civil, Geo and Environmental Engineering
- Electrical and Computer Engineering
- Informatics
- MakerSpace / Center for Innovation and Business Creation at TUM
- Mathematics
- Mechanical Engineering
- Munich School of Engineering
- Physics
- Partners from industry and research (DLR, LRZ, Fraunhofer and many more)



Follow up: TUM faculties where studium MINT participants enroll after the orientation semester.



Diversity

The proportion of women is far beyond the regular female share in the classic STEM disciplines. Most of the successful participants enroll in a regular, consecutive TUM bachelor's program, thereby profiting from the advantage of pre-existing knowledge and their university experience gained by participating in studium MINT.

Surveys among students show a high satisfaction with content and organization of the orientation program. About 90 % of the polled participants had their expectations completely fulfilled and 100 % would recommend the program to persons who are unsure with regard to their choice of a bachelor's program at TUM. The excellent reputation among participants and the unique position of the orientation semester in southern Germany results in a strong growth in numbers. It developed from 37 students in the first year (2014) to 420 in 2020.

Student voice

"As studium MINT participants we are per se ahead of the regular freshmen, at least at the beginning of our bachelor studies. Fortunately, I have been integrated very well into the MSE Student Council within studium MINT. Therefore I already have a lot of personal contacts at the beginning of my studies in the bachelor's program. Academic procedures like lectures, exercises, and homework are also familiar to me, as well as the premises at the Research Campus Garching. All in all I keep studium MINT in mind as a great experience!"

Johanna Gebhard (now studying Engineering Science)

In the upcoming summer semester 2021 the studium MINT will be paused. Nevertheless, the TUM considers the continuing of this semester of orientation in the well known format one year later.

MSE Student Council

Contact:
Student Council
Parkring 35
85748 Garching
Tel.: +49 89 289 52789

www.fs.mse.tum.de

The Student Council of the Munich School of Engineering (Fachschaft MSE) was founded in December 2010 and represents the approximately 1.000 B.Sc. and M.Sc. students of MSE. In addition, the Fachschaft MSE also advocates the students of the orientation program "Studium MINT".

The work of the Fachschaft MSE can be divided into three main areas: (i) The organization of events, (ii) the continuous improvement of study conditions, and (iii) student representation. All participation and contributions to the student council is on a voluntary basis. Members are rewarded with the possibility of improving university life in the long run, not only for themselves, but for all MSE students. New members who are willing to contribute to the development of MSE are always welcome and highly appreciated.

Each semester, the heads of the student council and the Fachschaft sections get elected by all MSE students. Currently, the student council represents nine focus sections: Freshmen, Evaluation & Lecture Notes, Finance, IT, PR, Events, Co-operation, Supervision of the Study Lounge (Quantum), and University Politics. Beyond this, the Fachschaft is providing a broad platform in a way that every student can work on exciting projects or join core teams, without the need of an official mandate.

Events

Some of the events the Fachschaft MSE has organized during the last years:

- Freshmen days: Each semester, about 250-300 new students start their studies at the MSE. The Freshmen section usually organizes two days with all kinds of entertainment for students from the different programs to get to know the city and their new fellow students. In 2020 this was sadly not possible due to the pandemic restrictions, but the Fachschaft MSE converted the event to an online get-together for all new students. Furthermore, every Freshman got an "Ersti-Tüte" with little gadgets useful for students. In addition the Fachschaft MSE created a welcome booklet with numerous important information and tips about university life and the city.
- Regular get-together events (Stammtisch): Once a month, the Events section arranges a get-together for all MSE students and a regular board game night every few weeks. Like the Freshmen Days, these events have been transformed to virtual meetings. The highly appreciated events are especially helpful for strengthening the connection between students in different programs and across cohorts.
- Student Council Weekend: Every semester, the Events Section organizes a weekend at a cottage for members of the Fachschaft MSE. While working on different kinds of projects, new members can get to know each other as well as the student council's work. The weekend in the summer term of 2020 had to be postponed, but the one in 2019 was very successful. We were able to revise our rules of internal procedure, improve some of our events like the Stadtralley and even work on new ideas as a poker tournament. Apart from that a lot of first semester students got in touch with the Fachschaft and are now active members or even leaders of our different sections.
- Other events: In 2019, we also organized a semester opening party and our annual christmas party. Again, the 2020 events have been transformed to virtual events. In the summer term of 2020, it was possible to arrange the MSEating, where students got to know each other by enjoying a picnic in a group of randomly selected peers. Apart from that, our Co-operation section, together with some volunteers, created an info event with different TUM student initiatives, e.g. TUM Boring and TUM Hyperloop. As this was a huge success, it is intended to continue with this event in the following years, too.

Improvement of study conditions

The Fachschaft MSE continuously tries to improve study conditions by providing lecture notes for all lectures, regularly evaluating the lectures, and passing on problems or ideas to the academic program office. This was especially important in 2020, when teaching during the first semester at the TUM was only available in a virtual format. The 2018 initialized peer mentoring program for the B.Sc. program, which was initialized in 2018, is still ongoing: students can ask peer mentors (students in a higher semester) for advice concerning their current and further studies. Furthermore, the Fachschaft MSE created a new tutor program for our new students in 2020, who did not have the opportunity to get to know each other in person. Every week for the first two months of the winter semester in 2020, a student in at least the third semester hosted a zoom meeting for his/her tutor group. In this way, the freshmen had the chance to get to know more people of their semester and had a person to contact with questions or problems concerning their studies. Due to the big success of the program, the Fachschaft MSE is going to continue the program next semester.

We also host a cloud service used by students to share course material, we organize voluntary soft skill courses as well as guided tours at companies relevant to MSE students. Each year, we award the best-performing lecturers the Top Teaching Trophy (T3), based on the evaluation results, to reward high-quality teaching at MSE.

Student representation

Via e-mail, phone, or attending the regular Fachschaft meetings, every MSE student can raise important issues when contacting the Fachschaft MSE. As the students' voice, the Fachschaft meets with the academic programs office at least once per semester, is in good contact with the Dean of Studies, and represents MSE students in the student parliament of the TUM (Fachschaftenrat). We have the ambition to solve problems as fast as possible. The Fachschaft MSE was and is actively involved in the reform of the TUM to the new school system. We are in active exchange with other faculties who will also be part of the new School of Engineering and Design (SoED), and have representatives in the different committees that are developing the future of the Fachschaft MSE. In addition, we are part of the Symposium of General Engineering Studies, where we talk to representatives of student councils from other universities (Hamburg, Bayreuth, Salzburg) that offer similar programs. Last year we also joined the IEA (Intercollegate Engineering Alliance), a union of universities all around the world with the ambition to connect and exchange knowledge. Other members are for instance Cambridge, MIT, Imperial College London or RWTH Aachen.

Internationalization

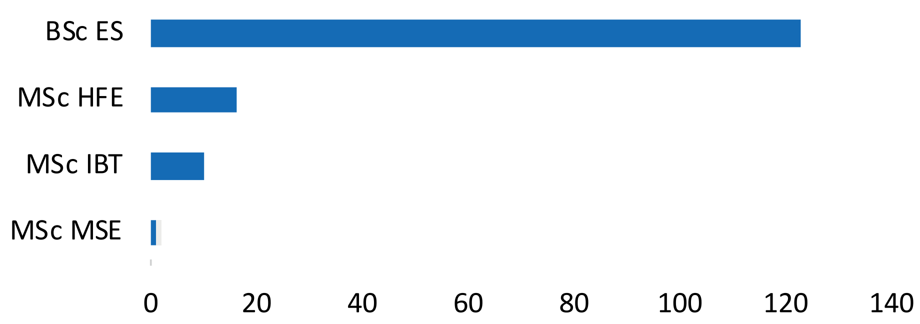
Gaining international experience is considered an important component in the academic education and personal development of students in all study programs at the Munich School of Engineering. Integrated in the service structures of the central TUM Global & Alumni Office, students of all MSE study programs have access to a wide range of opportunities for study stays abroad worldwide on all continents. In 2019/2020, the number of students taking advantage of this offer has again increased significantly. In particular, students in the bachelor's degree program Engineering Science exhibit a strong effort to incorporate an internationalization component into their curriculum.

The main internationalization programs used are Erasmus+ and TUMexchange.

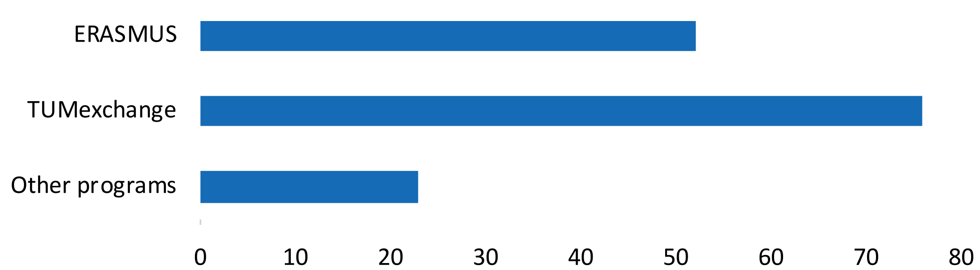
Erasmus+ focuses on the funding of study stays and internships in European countries. MSE has bilateral Erasmus+ agreements with renowned universities, e.g. with the Technical University of Denmark, the École Polytechnique and the Eidgenössische Technische Hochschule Zürich.

The TUM-internal internationalization program TUMexchange enables intercontinental study stays through numerous agreements with universities in all regions of the world.

Outgoing students by study program in 2019/2020



Outgoing students by mobility program in 2019/2020



Outgoing students by destination in 2019/2020


Stefan Hobmaier / TUM

Research Centers

TUM.Battery Network

Head:
Prof. Dr. Hubert A. Gasteiger
hubert.gasteiger@tum.de
Chair of Technical Electrochemistry
Department of Chemistry
Lichtenbergstr. 4
85748 Garching
Tel.: +49 89 289 13628

www.tec.ch.tum.de

Prof. Dr.-Ing. Andreas Jossen
andreas.jossen@tum.de
Chair of Electrical Energy Storage Technology
Department of Electrical and Computer Engineering
Karlstraße 45
80333 Munich
Tel.: +49 89 289 26967

www.ei.tum.de/ees

is an interdisciplinary network in the field of research and development on battery technology and storage. TUM.Battery was founded in 2018 by leading TUM researchers and institutes in the field of battery research to crosslink the researchers from different chairs and departments at TUM and to support the interdisciplinary exchange and networking.
https://www.mse.tum.de/battery

Based on a strong interdisciplinary approach, the entire spectrum of battery research is represented - ranging from fundamental physical properties of novel battery materials in the physics department and material synthesis in the chemistry department, over full-cell operations in the mechanical engineering department and finally leading to the cell manufacturing.

Motivation for research

The main objective of TUM.Battery is to provide a platform for scientific exchange and networking amongst the researchers at TUM who are working on different aspects of battery research, both in engineering and the natural sciences. In addition, the TUM.Battery website, as part of the MSE homepage, collates information and updates on publications and poster contributions from the individual partners, as well as news about activities of TUM.Battery. Members of the different chairs on the post-graduate level come together with the aim to present battery research at TUM to other researchers, industrial partners, and the wider audiences. The network also provides a great opportunity for young researchers, in particular Ph.D. students, to network with members of other faculties. So far, more than 25 collaborative publications have been published.

Current activities

Two projects which deal with lithium-ion batteries based on liquid and solid-state electrolyte systems, are highlighted below:

ExZellTUM III

Battery cells in electrical energy storage systems are currently the most expensive part in an electric vehicle, which will continue to be the case in the upcoming years. The central challenge of electromobility is an increased battery energy density with a simultaneous cost reduction. Novel anode and cathode active materials as well as an optimization of the production processes are necessary for this purpose. The “Centre of Excellence for Battery Cells at the Technical University of Munich” has gained competences in battery production to investigate the entire process chain by four research groups: the Chair for Technical Electrochemistry (TEC), the Chair of Electrical Energy Storage Technology (EES), the Institute for Machine Tools and Industrial Management (iwb), and the Advanced Materials Group at the Neutron Source Heinz Maier-Leibnitz (FRM II).

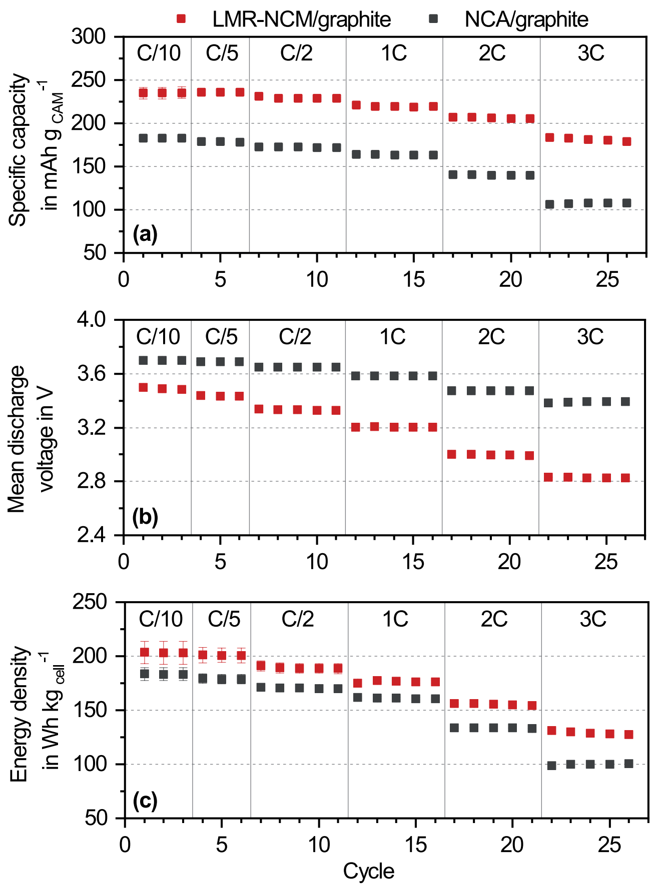
Within the framework of the funding initiative “Competence Cluster for Battery Materials (ExcellBattMat)” by the German Federal Ministry of Education and Research (BMBF), the research focus at the Excellence Battery Centre Munich lies on the material, chemical and electrochemical characterization and analysis, as well as the modeling of next-generation anode and cathode active materials. On the cathode side, the focus is on lithium- and manganese-rich NCM (LMR-NCM) materials that have a low cobalt content or even cobalt-free. Due to the high manganese content, LMR-NCM cathodes are more cost effective compared to common nickel-rich cathodes such as NCA or NCM811. On the anode side, silicon is investigated to replace conventional graphite anodes.

The successful collaboration among the four groups within the project ExZellTUM II (grant no.: 03XP0081) and the follow-up project ExZellTUM III (grant no.: 03XP0255) supported by the BMBF recently resulted in two joint articles in the Journal of the Electrochemical Society. Within this work, the high-capacity LMR-NCM cathode active material is for the first time employed in multilayer pouch cells (6-7 Ah) vs. graphite anodes and compared against established NCA/graphite cells. In a discharge rate capability test, as seen in Fig. 1, the LMR-NCM/graphite pouch cells reached approximately 30% higher specific capacities than the NCA/graphite cells. The energy densities on the cell level were still approximately11% higher, despite the lower mean discharge voltages of the LMR-NCM//graphite cells. At higher discharge currents, more pronounced heat generation of the LMR-NCM pouch cells was observed, which can be ascribed mostly to the open circuit voltage hysteresis of the LMR-NCM cathode active materials. These effects related to heat generation and gassing during formation and cycling can only be investigated in large-format cells, as they are not detectable in small-scale laboratory cells. This underlines the importance of the study of new active materials in both small-scale laboratory cells as well as in large-format cells in order to optimize both, the production of battery cells with new active materials and their operation.

After testing the discharge rate capability, the pouch cells went into an aging study with continuous C/2 charging and discharging. The cycling stability of the LMR-NCM/graphite cells was somewhat inferior due to their faster capacity and voltage fading, likely also related to electrolyte oxidation. This resulted in a lower energy density on the cell level after 210 cycles compared to the NCA/graphite pouch cells. The comparative evaluation of the two cell systems revealed that LMR-NCM proved to be a high-capacity cathode active material, which is environmentally benign and comparatively cheap because of its high manganese share compared to that of cobalt and nickel. Some of the long-term stability issues of LMR-NCM cathode active materials are currently being addressed by the manufacturer, and a new and improved generation of materials will soon be examined. Because of the heat generation for discharge rates above C/2, the application of LMR-NCM materials in large-format cells requires an optimization of the accompanying cooling system. In general, the class of LMR-NCM cathode active materials is more suited for high-energy rather than high-power applications. [1,2]

[1] D. Schreiner, T. Zünd, F. J. Günter, L. Kraft, B. Stumper, F. Linsenmann, M. Schüßler, R. Wilhelm, A. Jossen, G. Reinhart, and H. A. Gasteiger, “Comparative Evaluation of LMR-NCM and NCA Cathode Active Materials in Multilayer Lithium-Ion Pouch Cells: Part I. Production, Electrode Characterization, and Formation.” Journal of The Electrochemical Society 168 (3), 030507 (2021)

[2] L. Kraft, T. Zünd, D. Schreiner., R. Wilhelm, F. J. Günter, G. Reinhart, H. A. Gasteiger, and A. Jossen, “Comparative Evaluation of LMR-NCM and NCA Cathode Active Materials in Multilayer Lithium-Ion Pouch Cells: Part II. Rate Capability, Long-Term Stability, and Thermal Behavior.” Journal of The Electrochemical Society 168 (2), 020537 (2021)



Discharge rate capability test of ca. 5 Ah LMR-NCM/graphite and NCA/graphite pouch cells

Co-operation in the field of All-Solid-State Battery – ASSB – storage technology of the future

The increasing need for high-performance energy storage drives the further development of existing storage technologies. In particular, future developments in the field of electro-mobility enforce the development of novel storage solutions enabling higher storage capacities, longer durability and increasing security requirements compared to state-of-the-art lithium-ion-technology

Since 2018, the competences of TUM's research groups in battery sciences have been strengthened and extended to enforce the development of all-solid-state battery technologies at TUM, strongly supported by the Bavarian Ministry of Economic Affairs, Regional Development and Energy. This resulted in a highly productive co-operation between TUM and TUMint·Energy Research GmbH, founded in November 2019 as a subsidiary of TUM. TUMint·Energy Research GmbH is an interdisciplinary and application-oriented research facility located at the research campus Garching-Forschungszentrum. Its international team works in collaboration with numerous groups of TUM on the research and development of all-solid-state batteries - the next generation of storage technology.

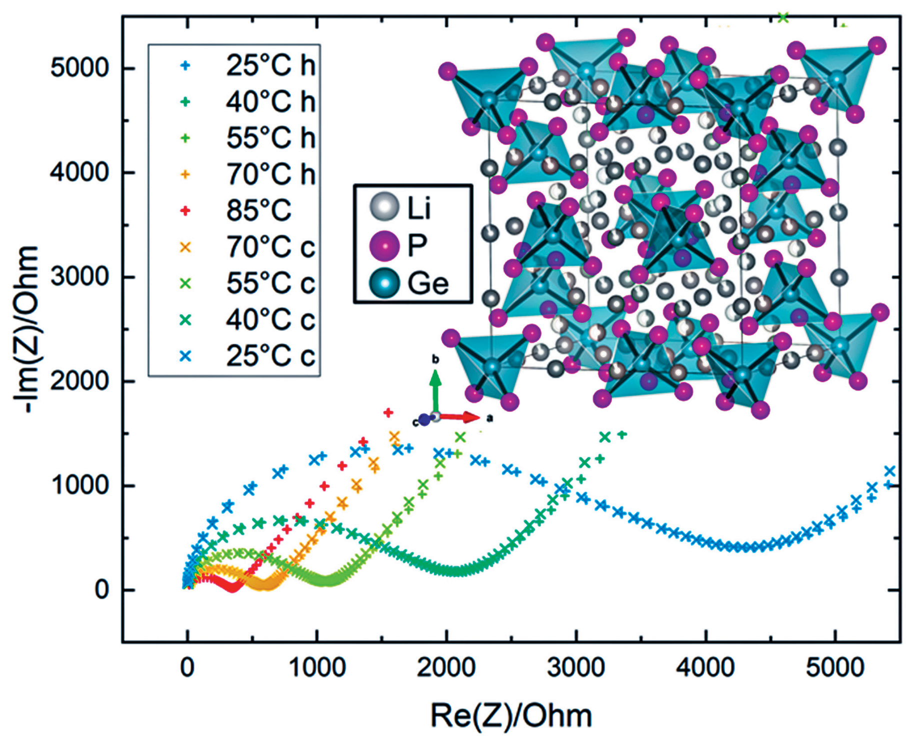
The initiative for ASSB storage technology currently involves eight research groups from four TUM departments. Four of them joined the project recently and contribute in the field of novel polymer materials and spun separator membranes as well as in the development of computational models and the simulation of electrochemical processes as well as thermo-mechanics inside the all-solid-state cells. The others partnered from the very beginning and are already reporting very exciting scientific results, some of which are presented below.

Synthesis – Chair of Inorganic Chemistry with Focus on New Materials

In the very beginning of the value chain for all-solid-state batteries, the first challenge is the development, engineering and synthesis of innovative materials. Prof. Dr. Fässler and his Chair of Inorganic Chemistry with focus on new materials have developed novel battery materials with special emphasis on lithium-ion conductors for their usage in all-solid-state batteries. By synthesizing new materials and their structural and electrochemical characterization, new insights in the conduction mechanism of lithium ions in solid electrolytes can be gained. In the center of research is the investigation of structure-property relationships in lithium phosphido-tetrelates and -trielates, which represent a new class of lithium ion conductors with conductivities up to 3 mScm-1. [3,4]

[3] S. Strangmüller, H. Eickhoff, D. Müller, W. Klein, G. Raudaschl-Sieber, H. Kirchhain, C. Sedlmeier, V. Baran, A. Senyshyn, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, and T. F. Fässler, „Fast ionic conductivity in the most lithium-rich phosphidosilicate Li14SiP6." Journal of the American Chemical Society, 141(36), 14200-14209 (2019)

[4] T. M. F. Restle, C. Sedlmeier, H. Kirchhain, W. Klein, G. Raudaschl-Sieber, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, T. F. Fässler, „Fast Lithium Ion Conduction in Lithium Phosphidoaluminates." Angewandte Chemie, 132(14), 5714-5723 (2020)



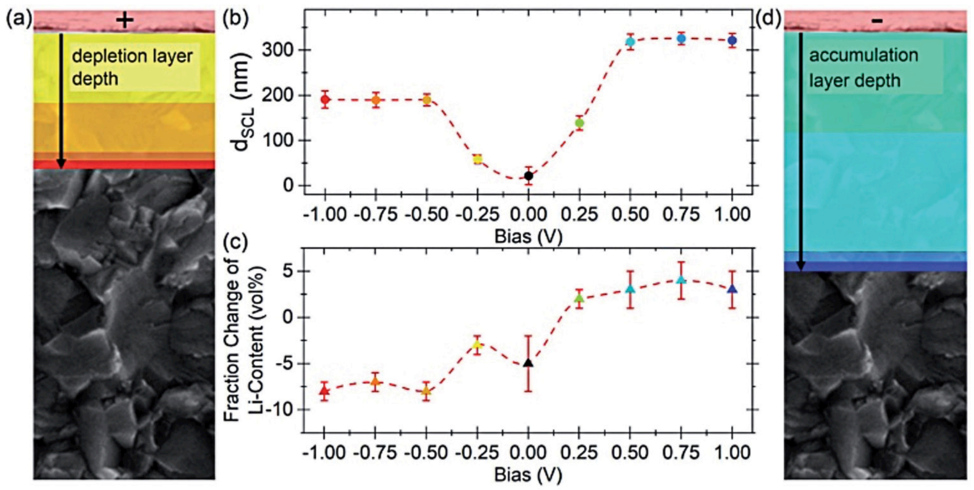
Investigation of solid electrolyte conductivity using impedance spectroscopy at different temperatures

Modelling – Chair of Physics of Energy Conversion and Storage (ECS)

Within the three chairs working on the development and validation of theoretical models for all-solid-state batteries, the group of Prof. Bandarenka from the Chair of Physics of Energy Conversion and Storage (ECS) in the Physics department investigates fundamental transport phenomena and electrochemical processes occurring in battery cells. The group recently revealed the nature of space charge layers (SCLs) in lithium conducting solid electrolytes. SCLs form at the interface of materials with a difference in electrochemical potential, similar to the concept of space charge regions in semiconductors. A high interface resistance was observed using electrochemical impedance spectroscopy [5], but an asymmetry in the formation of accumulation and depletion layers could be observed with in-situ spectroscopic ellipsometry. [6]

[5] L. Katzenmeier, S. Helmer, S. Braxmeier, E. Knobbe, and A. S. Bandarenka, „Properties of the Space Charge Layers Formed in Li-Ion Conducting Glass Ceramics." ACS Applied Materials and Interfaces, 13(4), 5853–5860 (2021)

[6] L. Katzenmeier, L. Carstensen, S. J. Schaper, P. Müller-Buschbaum, and A. S. Bandarenka, „Characterization and Quantification of Depletion and Accumulation Layers in Solid-State Li + -Conducting Electrolytes Using In Situ Spectroscopic Ellipsometry." Advanced Materials, 2100585 (2021)

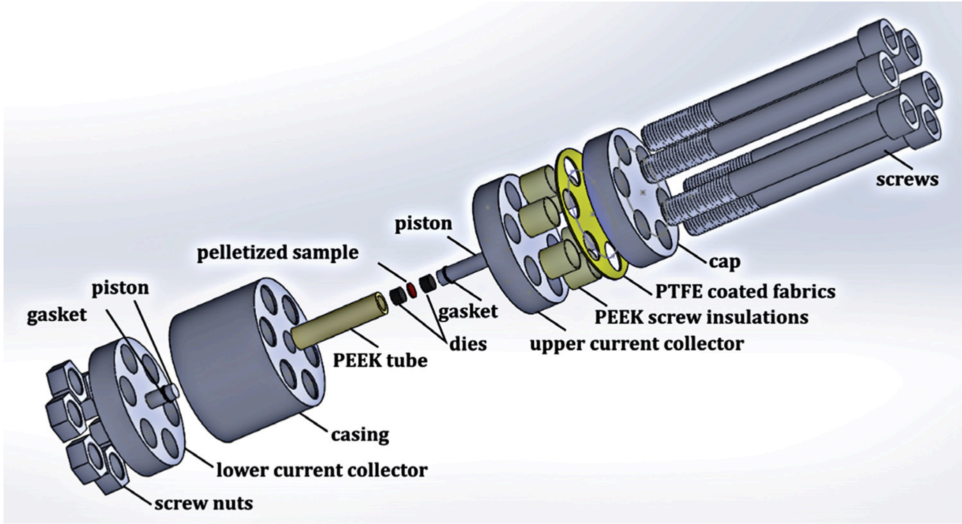


Schematic illustration of depletion and accumulation layer in solid electrolyte upon applied external bias.

Diagnostics – Chair for Technical Electrochemistry (TEC)

The development of all-solid-state test cell design and related cell diagnostic methods are the research focus at the Chair for Technical Electrochemistry (TEC) in the project "ASSB Bayern", continued within the co-operation with TUMint·Energy Research GmbH.

One essential part was the development and validation of a cell setup for high pressure impedance measurement. Using this cell, the new class of phosphide based solid electrolyte materials that was synthesized at the Chair for Inorganic Chemistry for New Materials, was evaluated. Furthermore, an innovative way to process powdered solid electrolyte in order to obtain sheet-type separators was investigated. Those sheet-type separators are necessary for all-solid-state pouch cell applications and enable the transition to pilot production of ASSB cells.

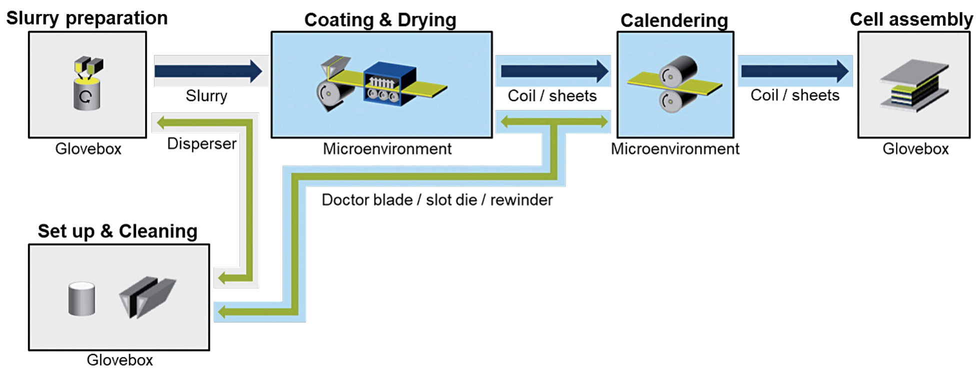


Development cell setup for high pressure impedance measurement for solid electrolyte investigations.

Production of all-solid-state batteries – The Institute for Machine Tools and Industrial Management (iwb)

The Institute for Machine Tools and Industrial Management (iwb) develops, coordinates, and implements novel fabrication concepts for all-solid-state batteries. The development of the production concept is the first and fundamental step for the production of large-format sulfide-based all-solid-state batteries. Suitable processes and equipment from material preparation to cell finalization were selected along the entire process chain.

To determine the properties of the components relevant to the production of all-solid-state batteries, the processes of layer fabrication were initially established on the laboratory scale. These include mixing, coating, drying, and pressing of separators and composite cathodes. Intermediate products such as slurry, wet and dry film as well as compressed components were characterized. The subsequent derivation of process windows by systematically varying the material composition as well as the process parameters lays the foundation for further research and the establishment of pilot-scale processes.



Process chain of solid-electrolyte production.

TUM.Hydrogen and Power-to-X Network

Head:
Prof. Dr.-Ing. Hartmut Spliethoff
spliethoff@tum.de
Dr.-Ing. Sebastian Fendt
sebastian.fendt@tum.de
Chair of Energy Systems

Department of Mechanical Engineering

Boltzmannstr. 15
85748 Garching
Tel.: +49 89 289 16270

www.es.mw.tum.de

The network was initiated in 2013 and officially launched as an interdisciplinary platform in 2019 by leading TUM researchers in the field of Power-to-X (PtX) and hydrogen technologies. Numerous chairs, research groups and institutes from various faculties such as chemistry, mechanical engineering, and electrical engineering as well as the school of management work together to jointly advance research in the area of Power-to-X and to use synergies between the research fields.

The transfer from research to application takes place through strong networking and collaboration with industry and business. On the one hand, individual projects are carried out in the core competence areas. On the other hand, cross-linked and interdisciplinary co-operative projects are implemented, which allow to bridge the gap between fundamental research and application.

The TUM.Hydrogen and PtX Network coordinates research on multiple topics related to hydrogen and PtX. The new joint website provides a platform for all participating partners to present their expertise and contributions to the research field:
https://www.mse.tum.de/ptx

Motivation for Research

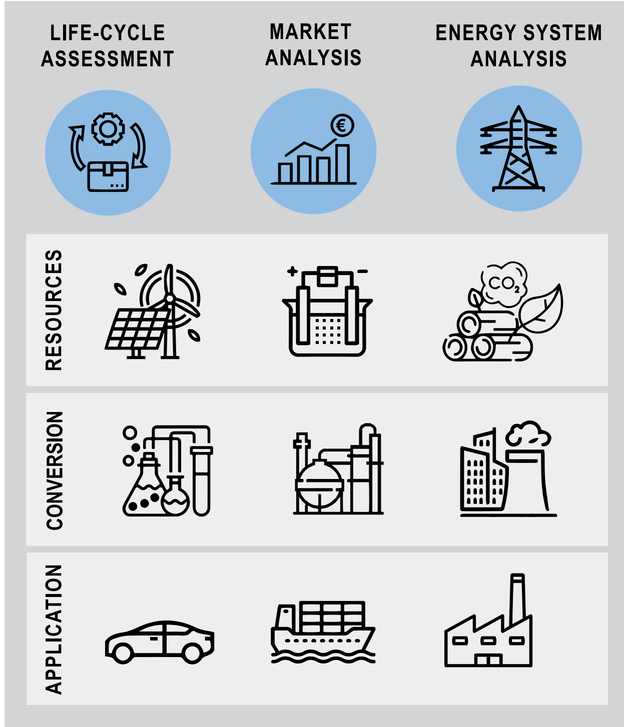
Technologies such as the production of heat, hydrogen or synthetic energy carriers from renewable power sources will play an important role in the context of the energy transition and the transformation of current energy systems. The research efforts of several groups at TUM is coordinated within the interdisciplinary network TUM.Hydrogen and PtX.

Given the ongoing climate change and the finite fossil fuel resources, PtX processes and water electrolysis will become increasingly important for a future sustainable energy system. Using wind and solar electricity, the electrochemical dissociation of water (water electrolysis) can produce hydrogen, which can serve directly as fuel for hydrogen fuel cell vehicles, for industrial applications (e.g. ammonia synthesis) or as a renewable energy storage medium.

Nevertheless, hydrogen production by electrolytic processes currently accounts for only about 4% of the worldwide annual hydrogen production, but this share is expected to increase in response to hydrogen strategies in Germany, at EU level and on a worldwide scale.

Understanding PtX systems in their complete value chain will play a central role in the transformation of the current energy system. PtX in this context represents the production of gaseous or liquid energy carriers such as hydrogen, methane, methanol, synthetic fuels, or basic chemicals („X“) from renewable electricity („Power“).

For a long time, TUM has contributed to advances of various technologies: from the areas of **resources, conversion** and subsequent **application and utilization**. From fundamental research in the field of materials, process technologies in electrochemistry and electrical engineering, including the integration into future energy systems, the entire value chain, which is essential to be considered.



In addition to technical issues, business and innovation management and system-level considerations of the value chain play a key role in all phases of technology implementation. Thanks to a multitude of competencies and the links between relevant actors, TUM can conduct future-oriented and application-related research that meets these interdisciplinary challenges.

Research – From fundamental, laboratory research to pilot-scale application to integration in the energy system

At TUM more than 22 chairs and institutes with more than 80 employees at six departments currently work in the field of hydrogen and PtX technologies. Additionally, co-operation exists with more than 60 partners from industry and research beyond TUM. The highlights of interdisciplinary research in the four focus areas are provided in the following:

Resources

Within the research area of resources, material, and energy flows for PtX systems are investigated. This includes all input streams used for PtX systems (electricity, heat and educts, such as water, carbon or CO_2 source e.g. from biomass, waste, cement industry etc.). Methods and technologies for CO_2 and H_2 production also belong to this area. The main focus is on the investigation of CO_2 separation processes, electrolysis for hydrogen production and the provision of carbon-containing synthesis gases from e.g. Biomass.

The **Institute of Plant and Process Technology** (APT) investigates the production of sustainable synthesis gases by means of CO_2 filtration from air, water and renewable electricity with high temperature co-electrolysis (see Project: Kopernikus-Project P2X). Synthesis gas, usually generated from natural gas, serves as educt for the production of different downstream products, such as DME, synthetic fuel or synthetic natural gas. The goal is to develop a more sustainable synthesis gas generation by the integration of electrolysis as a climate-neutral solution.

Furthermore, the **Chair of Energy Systems** (LES) works on the supply of carbon-containing synthesis gases to produce synthetic fuels (simulative and experimental). At LES, the provision of carbon-containing synthesis gases for the production of synthetic fuels is investigated using simulations and experiments within the framework of research projects. Several pilot plants for the gasification of waste and biogenic solid fuels are available for this purpose. The entire spectrum from gasification kinetics to the demonstration of the entire process chain is covered: biomass → synthesis gas → conversion.

The **Wind Energy Institute** (WEI) conducts research on green electricity from wind energy to produce renewable hydrogen. Since there are still many scientific and technological challenges to overcome, the penetration of wind energy by reducing its cost and mitigating its impacts are crucial. To contribute to the achievement of these goals, the Wind Energy Institute at TUM works on basic scientific and application-oriented problems, often in close collaboration with industry. Areas of specific expertise of the Institute embrace all main wind-energy-relevant scientific disciplines, including aerodynamics, structures, dynamics, materials, controls, with a strong focus on multi-disciplinary and systems-engineering point of view.

The **Chair of Technical Electrochemistry** (TEC) has a high level of expertise in electrolysis solutions for the production of hydrogen from renewable energy. In the field of PtX, TEC is performing research on solutions for proton exchange membrane (PEM) water electrolyzers. By using renewable energies, it is possible to produce green hydrogen via PEM water electrolysis. The research at TEC focuses on the design of membrane electrode assemblies (MEAs) and of porous transport layers (PTLs), which are central components in PEM water electrolyzers. Topics include fundamental aspects (e.g. understanding of reaction mechanisms of novel catalyst materials) as well as applied research (e.g. reduction of catalyst loadings in MEAs, evaluation of MEA lifetime) (see projects: Kopernikus-Project P2X).

Conversion
Conversion describes the material conversion of hydrogen and CO_2/CO into higher energy sources and the possible subsequent production of synthetic fuels and basic chemicals. The TUM.Hydrogen and PtX network focuses on research on methanation, production of methanol and other synthetic fuels and basic chemicals.

The **Institute of Plant and Process Technology** (APT) conducts simulations and optimization of different plant options for the integrated production of different downstream products from sustainable syngas. The synthesis gas generation is directly linked to the product processing. Depending on the type of product (e.g. DME, synthetic fuel or synthetic natural gas), different synthesis gas ratios are necessary. For the required ratios, individual process designs are developed to increase the sustainability of product manufacturing. The synthesis gas processing for the synthetic fuel production, developed within the Kopernikus-Projekt P2X, is carried out in a Fischer-Tropsch-reactor forming long-chain hydrocarbons, which are subsequently converted into the desired product. These and other process options for an integrated production of different downstream products are simulated to optimally combine the different process steps and to reach higher production volumes (see projects: Kopernikus-Project P2X).

The focus of research in the area of conversion at the **Chair of Energy Systems** (LES) is divided into two parts. On the one hand, high-temperature solid oxide electrolysis cells (SOEC) are investigated. On the other hand, the catalytic synthesis of methane is researched. For this purpose, various reactor concepts for different process configurations (CO_2-PtX, biomass gasification with electricity integration, innovative biogas conversion) are examined and optimized. This research is based on simulations as well as experiments. (see Project: BioCORE). The Chair of Energy Systems also models the production of synthetic fuels, especially methanol and OME, to integrate them optimally into the German energy system (see projects: e2Fuels).

The research at the **Chair I of Technical Chemistry** (TC1) in PtX focuses on the structural and kinetic characterization of catalysts for the hydrogenation of carbon oxides. To understand and to improve the hydrogenation catalysts in terms of their catalytic properties, comprehensive fundamental research on structure-activity relationships is necessary. The hydrogenation reactions in the PtX processes are generally characterized by their high heat of reaction. Therefore, the kinetic description of product formation rates and, based thereon, application-related reactor modeling studies are of special interest.

The **Chair of Urban Water Systems Engineering** (SWW) is researching the microbiological methanation of hydrogen and carbon dioxide in a trickle bed reactor under thermophilic conditions. As the end product, CH4 should be as pure as possible.
The goal is to develop a simple and robust system for decentralized operation e.g. on wastewater treatment plants in order to use their existing infrastructure (gas storage, CHP, etc.) for energy storage. The gas-tight but pressureless system is inoculated with digestate from the digester of sewage sludge or biogas plants.

SWW / TUM

■ **Pilot plant for methanisation from waste water at the campus in Garching**

The **Professorship Chemical Process Engineering** (CTV) is concerned with the development of new PtX processes in methanol down-stream chemistry and is accordingly at the very end in the value chain. Based on the synthesis of methanol and formaldehyde, new chemical processes for the production of synthetic diesel fuels OME are also being developed and tested (see projects: e2Fuels and NaMoSyn).

Utilisation and Application
Within this research area, the application and use of the PtX products: hydrogen, methane, methanol, or synthetic fuels is being investigated. The utilization includes all fields of application of PtX products. In addition to engine use, turbine injection and electrochemical reconversion (e.g. use in the chemical and process industries) but also material use are researched.

Reducing greenhouse gases in the mobility sector is one of the most important challenges to stop climate change. Besides battery technology, hydrogen fueled vehicles are in the focus of research and development. Especially for long-distance commercial vehicles, the hydrogen fuel cell is an ideal solution. For this purpose, the Institute of **Plant and Process Technology** (APT) develops a highly efficient hydrogen tank based on the promising storage technology of cryogenic compressed hydrogen gas (CcH_2) that enables high storage densities.

Internal Combustion Engines can be used to apply synthetic fuels in propulsion and replace by electricity production in a cost- and energy-efficient way and with the lowest pollutant emissions. The modification of engine concepts for new fuels will further improve efficiency and exhaust after-treatment significantly compared to conventional fuels. In various applications combustion engines are increasingly combined with electric drives. This makes it necessary to develop hybrid systems, which can fulfill the ambitious requirements of a future sustainable energy economy. The **Institute of Internal Combustion Engines** (LVK) investigates economical, efficient and low-emission use of synthetic fuels for locomotion and power generation (see projects: e2Fuels, MethQuest and NaMoSyn).

The research of the Associate **Professorship of Thermo-Fluid Dynamics** (TFD) group focuses on thermoacoustic combustion instabilities. These impair the security and reliability of gas turbines and rocket engines as well as domestic or industrial burners. In order to analyze and control these instabilities, fluid mechanics, acoustics and combustion science are combined in an interdisciplinary approach with methods of system identification and control theory. Intensive exchange with colleagues from research institutes in- and outside Europe furthers our efforts.

Research at the **Chair of Technical Electrochemistry** (TEC) regarding the usage of PtX products focuses on proton exchange membrane (PEM) fuel cells to generate electrical energy. Topics include catalyst synthesis and catalyst layer design based on platinum group metals (PGM) as well as the development and characterization of PGM-free catalyst materials. Furthermore, transport processes in catalyst and gas diffusion layers are investigated and optimized. Performance and durability testing with in situ and ex situ diagnostics is performed, to gain a deeper understanding of degradation mechanisms.

For ecological and economic reasons, renewable alternatives to conventional jet fuel have moved into the focus of interest of the aviation industry. Technology options with promising long-term potential are of particular interest for the work at **Bauhaus Luftfahrt**. Advanced biofuel production from residue and waste streams and non-biogenic approaches, such as solar fuels, Power-to-Liquid (PtL) and hydrogen, represent important research topics in this context.

System and Market Studies

System studies primarily serve to forecast future developments and evaluate technologies and alternatives. With their help, market potential can be estimated, and the ecological and economic effects can be calculated using e.g. Life-Cycle Assessment (LCA).

The **Chair of Energy Systems** (LES) uses energy system modeling in a European context to evaluate the need for PtX in an integrated energy system. This energy system modeling and operational planning of different types of power plants helps to define techno-economic framework conditions and to determine the potential of technologies in the energy supply.

The **Chair of Renewable and Sustainable Energy Systems** (ENS) develops and operates state-of-the-art energy models. In the field of hydrogen, ENS is especially active in the Kopernikus-Project P2X project (phase I and II) and in the IEA/ETSAP project. ENS has a European wide energy model based on the energy modeling software urbs, which enables a European perspective on the future energy systems. A central question lies on the development of optimal infrastructure and understanding the competition between power and hydrogen transport. The chair is also strongly involved in understanding the sector coupling. Here again the competition between different infrastructure is conducted. A key question is whether hydrogen as a final energy carrier will be realized also for households and smaller consumers. Part of this work is carried out in close collaboration with MSE, especially the CoSES (Center for Combined Smart Energy Systems) laboratory system, where there is hope to equip it with hydrogen infrastructure soon (see projects: Kopernikus-Project P2X).

The Institute for **Electrical Energy Storage Technology** (EES) investigates the use of PtX technologies (electrolysis, hydrogen storage and fuel cell) for grid-scale storage applications. With the aim to improve performance, degradation behavior and efficiency, the following investigations are conducted: characterization and modelling of PtX components, time-series simulation of PtX components, modelling of hybrid storage concepts (PtX + Battery) and optimization of system dispatch. Characterization of PtX components is mainly conducted at the interface with partnering institutes (ZAE Bayern, TEC). Currently an open-source simulation tool for time-series evaluations in combination with optimization techniques is developed, which aids to conduct economic performance analyses. Furthermore, a hybrid-storage concepts is developed from scratch with an optimal component layout and best fitting operation strategy.

The **Chair of Strategy and Organization** (CSO) develops business models, innovation and go-to-market strategies for PtX products and services. In the field of interdisciplinary energy storage research the development of specific use cases, taking into account economic and regulatory framework conditions, is used to evaluate which stationary storage can be used in an economically useful way. Innovation and market introduction strategies are investigated to reduce costs and increase customers‘ willingness to pay for sustainable products or services.

Network for Renewable Energy

Head:
Prof. Dr. Peter Müller-Buschbaum
muellerb@ph.tum.de
Chair of the Institute of Functional Materials
Department of Physics

James-Franck-Str. 1
85748 Garching
Tel.: +49 89 289 12452

www.nrg.mse.tum.de

The Network for Renewable Energy (NRG) consists of multiple chairs at TUM to foster inter-faculty research on renewable energy. NRG was originally founded within TUM.Energy network. Currently, the Munich School of Engineering (MSE) is the umbrella organization containing the inter-faculty research platform TUM.Energy alongside to the teaching offered at MSE. The network focuses on sun, wind, biomass, water and other renewable energy sources, as well as their efficient distribution and use, with the aim to achieve a sustainable energy supply for the future. Regular meetings within the network take place to foster active communication between the different research groups.

Headed by Professor Müller-Buschbaum, NRG consists of a large number of activities, ranging from nanoelectronics and material research, microbiology and theoretical chemistry over biomass power production, to wave and solar energy systems and more. Some examples are given below: A new scalable production technique of metallic nanoparticles with a high electrocatalytic activity is used in fuel cells and electrolyzers. The promising properties of phosphide-based solid electrolytes are investigated for all-solid-state batteries, a comprehensive spectrum of renewable energy systems including various electrical components is investigated for a stable future electrical power system. Urban building envelopes in terms of climate-neutral building stocks that use solar energ y and greening are studied for a high quality built environment.

Ni-Al catalysts for CO_2-methanation are investigated for the application within the power-to-gas concept, CO_2-reduction to fuels on oxide derived copper electrodes and patterned photoelectrodes are characterized, novel organic and perovskite solar cells in operation are tested in laboratory measurements and space environment, and the enhancement of flame dynamic simulations using machine learning to improve the understanding of combustion instabilities are selected.

Top-down synthesis of Pt/C oxygen electro-reduction catalysts

Recently, the Bandarenka group developed a simple and scalable technique to produce metallic nanoparticles, which in turn is used in renewable energy technologies such as fuel cells and electrolyzers.[1] This unique and easy electrochemical method enables the production of Pt nanoparticles with desired sizes and shapes (in the range from ~2 to ~10 nm). In brief, an alternating potential (AC voltage) is applied to a metal wire immersed in basic solution, which consequently generates metallic nanoparticles (Fig. 1a).

Furthermore, the size and shape of the Pt nanoparticles can be tailored by changing simple parameters such as frequency, the shape of the applied potential or the electrolyte concentration. For instance, application of a sinusoidal AC voltage with lower frequencies results in cubic nanoparticles; whereas higher frequencies lead to predominantly spherical nanoparticles with surface defects. On the other hand, the amplitude of the sinusoidal signal was found to affect the particle size; the lower the amplitude of the applied AC signal, the smaller the resulting particle size.

The results from various techniques such as electron microscopy and tomography confirm the presence of high degree of concavities and defects on the surface of formed Pt nanoparticles (Fig. 1b). [2] Moreover, the results from Pt model catalyst surfaces have demonstrated that such surface defects, in particular surface concavities, can improve the oxygen reduction reaction kinetics, taking place at the cathode of the hydrogen fuel cells. Hence, the activity of prepared Pt/C catalyst towards the ORR was studied. Pt/C catalysts prepared by this approach showed ~0.71 A/mg mass activity towards the oxygen reduction reaction, which is nearly two times higher than the state-of-the-art commercial Pt/C catalyst (0.42 A/mg).

Taking into account both the uniqueness and simplicity of the developed synthetic method and high electrocatalytic activity, this top-down approach offers an alternative route to conventional wet chemical synthesis of nanoparticles.

a)
b)

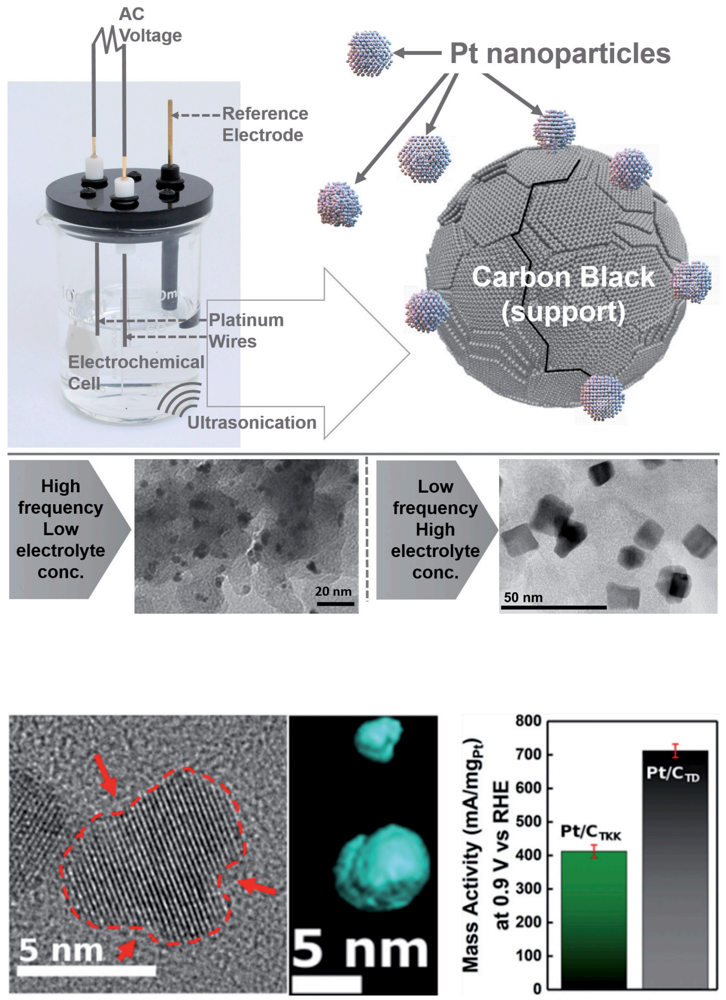


Fig. 1: (a) Schematic description of the simple and scalable top-down synthetic procedure for production of Pt nanoparticles supported on carbon. The lower images highlight how the applied potential frequency and the electrolyte concentration can be changed to govern the shape of formed nanoparticles.
(b) The ORR activity of Pt nanoparticles with high density of surface concavities. High resolution TEM and 3D Tomography images with mass activity of the Pt nanoparticles are shown in comparison to commercial Pt/C catalyst

[1] J. Fichtner, S. Watzele, B. Garlyyev, R. Kluge, F. Haimerl, H. El-Sayed, W.-J. Li, F. Maillard, L. Dubau, R. Chattot, J. Michalicka, J. Macak, W. Wang, D. Wang, T. Gigl, C. Hugenschmidt, A.S. Bandarenka, "Tailoring the Oxygen Reduction Activity of Pt Nanoparticles through Surface Defects: A Simple Top-Down Approach," ACS Catal., vol. 10, no. 5, pp. 3131–3142, 2020

[2] B. Garlyyev, S. Watzele, J. Fichtner, J. Michalička, A. Schökel, A. Senyshyn, A. Perego, D. Pan, H. El-Sayed, J.M. Macak, P. Atanassov, I.V. Zenyuk, A.S. Bandarenka, "Electrochemical top-down synthesis of C-supported Pt nanoparticles with controllable shape and size: mechanistic insights and application," Nano Res., 2020, doi: 10.1007/s12274-020-3281-z

Understanding lithium ion diffusion in the new family of phosphide-based ion-conductors

The understanding of the structural-property relationships in ion-conducting solid electrolytes is crucial for the development and investigation of new materials, which can act as solid electrolytes in an all-solid-state battery. Recently, phosphide-based materials were introduced with the compounds Li_8SiP_4 and Li_8GeP_4 as a new class of solid-state ionic conductors by the Fässler group. These materials exhibit a rather simple structure based on a close packing of phosphorus atoms with isolated silicon or germanium phosphorus tetrahedra and lithium atoms occupying partially both tetrahedral and octahedral voids. Investigations to expand these materials by increasing the lithium concentration led to the discovery of the superionic conductors $Li_{14}SiP_6$ and $Li_{14}G_eP_6$ (Fig. 2a).[3,4] High-purity bulk materials of these conductors can be easily obtained by a ball milling synthesis. These materials show ionic conductivities of 1.1 x 10-3 S/cm and 1.7 x 10-3 S/cm, respectively. Powder neutron diffraction experiments at the SPODI at FRMII and one-particle calculations revealed the lithium conduction pathway inside the structures (Fig. 2a). Lithium ion diffusion occurs preferentially by jumps via face-sharing octahedral and tetrahedral voids. Furthermore, this material class was expanded by the aliovalent substitution with aluminum. The substitution lead to the discovery of the superionic conductor Li_9AlP_4, which is the first representative of lithium phosphidoaluminates.[5] This material shows so far the highest ionic conductivity of 3.0 x 10-3 S/cm at room temperature of all phosphide-based materials. The higher lithium concentration in Li_9AlP_4 leads to an energy landscape flattening of the lithium sites, which is indicated by a more equal occupancy of octahedral and tetrahedral voids compared to the related phases Li_8SiP_4 and Li_8GeP_4. Additionally, with Li_3AlP_2 a second lithium phosphidoaluminate was investigated, where the lithium atoms are occupying only tetrahedral voids and no octahedral voids. This material does not show any ionic conductivity.[6] Hence, it is necessary to have lithium atoms occupying tetrahedral as well as octahedral voids inside phosphide-based materials to enable ion conduction.

[3] S. Strangmüller, H. Eickhoff, D. Müller, W. Klein, G. Raudaschl-Sieber, H. Kirchhain, C. Sedlmeier, V. Baran, A. Senyshyn, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, T. F. Fässler, "Fast Ionic Conductivity in the Most Lithium-Rich Phosphidosilicate Li14SiP6", J. Am. Chem. Soc. 2019, 141, 14200–14209, 2019

[4] S. Strangmüller, H. Eickhoff, G. Raudaschl-Sieber, H. Kirchhain, C. Sedlmeier, L. van Wüllen, H. A. Gasteiger, T. F. Fässler, "Modifying the Properties of Fast Lithium-Ion Conductors—The Lithium Phosphidotetrelates Li14SiP6, Li14GeP6, and Li14SnP6," Chem. Mater., vol. 32, no. 16, pp. 6925–6934, 2020

[5] T. M. F. Restle, C. Sedlmeier, H. Kirchhain, W. Klein, G. Raudaschl-Sieber, V. L. Deringer, L. v. Wüllen, H. A. Gasteiger, T. F. Fässler, "Fast Lithium Ion Conduction in Lithium Phosphidoaluminates," Angew. Chem. Int. Ed., vol. 59, no. 14, pp. 5665–5674, 2020

[6] T. M. F. Restle, J. V. Dums, G. Raudaschl-Sieber, T. F. Fässler, "Synthesis, Structure, Solid-State NMR Spectroscopy, and Electronic Structures of the Phosphidotrielates Li 3 AlP 2 and Li 3 GaP 2," Chem. Eur. J., vol. 26, no. 30, pp. 6812–6819, 2020

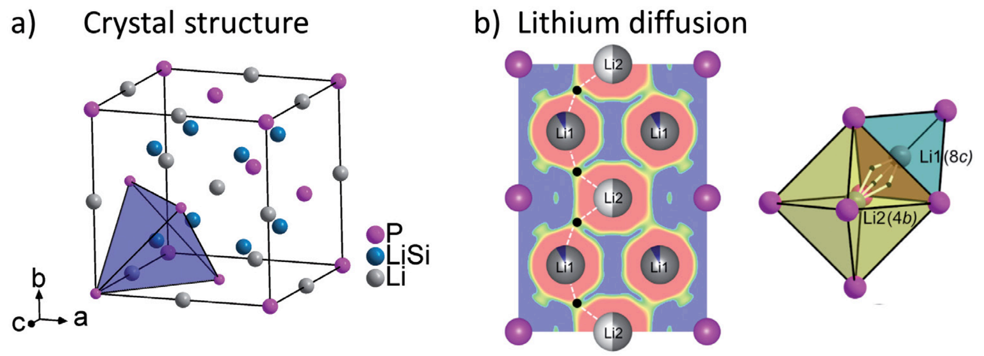


Fig. 2: a) Crystal structure of Li14SiP6. The phosphorus atoms form a cubic close packing and lithium occupies tetrahedral and octahedral voids. Isolated silicon phosphorus tetrahedra are highlighted in blue. b) Using the maximum entropy approach and applying the one-particle potential formalism, lithium diffusion pathways are obtained. The pathways occur preferably by jumps via adjacent octahedral and tetrahedral voids.

Laboratory for Mechatronic and Renewable Energy Systems (LMRES)

Efficiency, reliability, and robustness are key features of future renewable energy systems (RES) to guarantee a safe and stable operation of the power system and to ensure a sustainable supply of the world with affordable electrical energy. In view of the increasing number of renewable energy sources, the self-stabilizing effect of the large inertias of conventional generators is diminishing. Therefore, the future generation of RES must progressively contribute to the safety and stability of the future electrical power system. For that, future RES must become more efficient, reliable and robust than conventional energy sources. Moreover, these RES must be operational even under critical operating conditions such as unbalanced loading and/or short-circuits of one or more phases. These challenges are the drivers for the research and teaching activities of the Hackl group in the Laboratory for Mechatronic and Renewable Energy Systems (LMRES) at the Munich University of Applied Sciences (LMRES was formerly part of TUM`s MSE research group Control of Renewable Energy Systems (CRES)).

Fig. 3. Overview of the broad spectrum of mechatronic and renewable energy systems covered by the central research activities of the Hackl group.

Central research and teaching activities at LMRES are modeling, simulation, optimization, control, and experimental validation of the considered mechatronic and renewable energy systems, where the most dominant machine topologies (e.g. singly- or doubly-fed induction machines, electrically excited synchronous machines, reluctance synchronous machines, and multi-phase machines), converter topologies (e.g. two-/three-/five-level converters, modular multi-level converters (M2C) and modular multilevel matrix converters (M3C)) and grid filter topologies (e.g. L-,LC- and LCL filter) were considered. Hence, a comprehensive spectrum of the electrical components of today's and future mechatronic and renewable energy systems is covered (Fig. 3).

Main research foci of the Hackl group are (i) nonlinear, switched and dynamical modeling in state space, (ii) condition monitoring and fault detection, (iii) design of intelligent, robust, and fault-tolerant control, and (iv) efficiency enhancement and loss minimization of individual components and the considered overall systems. Since 2019, more than 30 peer-reviewed scientific contributions in books, journals and conference proceedings have been published [7,8].

[7] A. Birda, J. Reuss and C.M. Hackl, "Synchronous optimal PWM for synchronous machines with highly operating point dependent magnetic anisotropy", IEEE Trans. Ind. Electron., vol. 68, no. 5, pp. 3760–3769, 2021

[8] C.M. Hackl and M. Landerer, "Modified second-order generalized integrators with modified frequency locked loop for fast harmonics estimation of distorted single-phase signals", IEEE Trans. Power Electron., vol. 35, no. 3, pp. 3298–3309, 2020

Modeling approaches for residential buildings, vertical greenery, photovoltaic façades and urban microclimate

The Hemmerle group Cleanvelope (sponsored by the Bavarian Climate Research Network, bayklif) investigates how urban building envelopes can be energetically activated to use solar energy and promote a climate-neutral building stock while balancing competing installations like roof and façade greening as climate change adaptation strategies and without compromising the architectural quality of the built environment.

This requires a balancing and prioritization of different technological measures and design options for building envelopes, considering urban planning, architecture, energy, climate, biodiversity, and other aspects beyond the envelope context. Therefore, a holistic, district-scale design and decision support in early design stages based on a multi-criteria decision analysis (MCDA) approach in order to account for the complexity of design decisions has been developed. When used during early design stages, it can promote district concepts with high energy efficiency, and excellent climate performance and resilience.

The research aim of representing and studying energy flexibility in a sector-coupled district context has led to the development of model features as part of the overall energy model structure "CleanMod" in Fig. 4. In particular, solar gains as input to the heating demand models are calculated in a consistent way with the PV yield of the buildings' envelopes considering the surrounding environment as shading context. The model for the dynamic thermal behavior of apartments of multi-family buildings has been integrated relying on the resistance-capacitance approach [9]. However, a large-scale implementation of PV modules in urban facades alters the urban radiation balance and may contribute to the urban heat island effect. Therefore, a simulation-based workflow based on the modeling platform Grasshopper has been developed to quantify the mutual effects between PV facades and urban microclimate at district scale [10]. The workflow will be coupled to the "CleanMod" tool and used for parametrical studies as well as specific case studies.

Furthermore, an analysis of options, opportunities, and challenges for municipalities to implement climate protection and climate change adaptation actions on the local level has revealed well established processes and powerful instruments. A governance process to integrate solar energy and greening into a neighborhood redevelopment approach has been outlined and will be worked out in co-operation with the city of Munich.

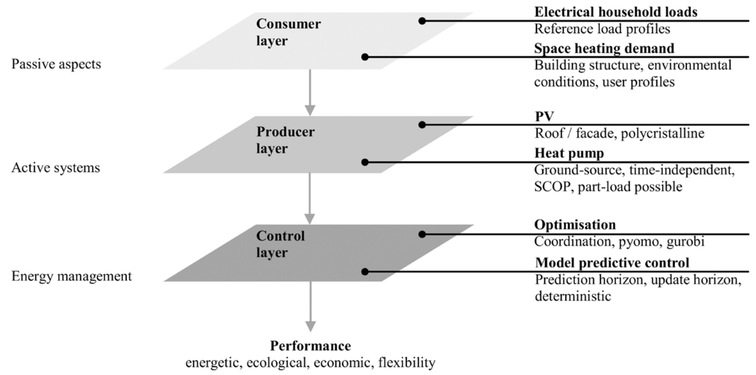


Fig. 4: Model components of developed tool "CleanMod"

[9] L. Bogischef, M. De-Borja-Torrejon, and C. Hemmerle, "Residential buildings as a flexibility component in the district network - Development of a modelling approach / Wohngebäude als Flexibilitätsbaustein im Quartiersverbund – Entwicklung eines Modellierungsansatzes," Technical University of Munich, 2020

[10] Fassbender, E.; Hemmerle, C. (2020). Modeling workflow for simulating the interdependencies between vertical greenery systems, photovoltaic facades and urban microclimate. Proceedings 15th Conference on Advanced Building Skins. ISBN 978-3-9524883-0-0

Exploring CO_2 methanation with Ni-Al catalysts for power-to-gas

Due to strong population growth and steadily increasing energy demand, the topic of renewable energies is more in focus than ever before with regard to global warming. Alternative pathways must be developed to effectively store renewable energy. One approach that has received much attention in recent years is the so-called power-to-gas (PtG) concept. This is where the energy from renewable sources is converted into hydrogen by means of water electrolysis, which is then converted with carbon dioxide into synthetic natural gas (SNG) in the so-called methanation process (Fig. 5). The Hinrichsen group works on making the methanation process more viable for potential industrial application by developing highly active, selective, and stable methanation catalysts. In this context, they compared Ni-based materials prepared by various techniques like co-precipitation, impregnation and chemical vapor deposition in terms of their catalytic performance. In recent years, co-precipitated Ni-Al materials were optimized with regard to industrial application by means of improving their catalytic activity as well as their thermal stability by promotion with manganese and/or iron [11], for example. The stability of the developed catalysts was tested via artificial aging studies coupled with detailed material characterization to gain an understanding of prevailing deactivation mechanisms under operation conditions on the nanoscale [12]. Besides catalyst synthesis, they developed an intrinsic kinetic model for CO_x methanation to describe the kinetics over a co-precipitated Ni-Al catalyst under industrially relevant conditions [13], where feed gas derived from biomass gasification, for example, may be a complex mixture of carbon oxides, steam, and hydrogen, varying in composition. To further investigate the impact of sulfur components typically present in trace concentrations in synthesis gas, research activities in this field focused on the effect of sulfur poisoning in in-situ and ex-situ poisoning techniques on material properties and catalyst activity in lab-scale experiments.

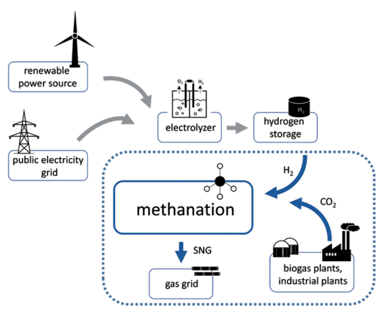


Fig. 5: CO_2 methanation in the context of the power-to-gas (PtG) concept.

Ni-Al catalysts are a promising approach for methanation, which can be influenced in a targeted manner on the catalyst structure by adjusting the synthesis and material treatment parameters. A precise understanding of this form of catalysis can help establish the power-to-gas concept as an environmentally friendly contribution to the energy transition.

[11] T. Burger, F. Koschany, A. Wenng, O. Thomys, K. Köhler, and O. Hinrichsen, "Simultaneous activity and stability increase of co-precipitated Ni–Al CO_2 methanation catalysts by synergistic effects of Fe and Mn promoters," Catal. Sci. Technol., vol. 8, no. 22, pp. 5920–5932, 2018

[12] S. Ewald, M. Kolbeck, T. Kratky, M. Wolf, O. Hinrichsen, "On the deactivation of Ni-Al catalysts in CO_2 methanation," Applied Catalysis A: General, vol. 570, pp. 376–386, 2019

[13] T. Burger, P. Donaubauer, and O. Hinrichsen, "On the kinetics of the co-methanation of CO and CO_2 on a co-precipitated Ni-Al catalyst," Applied Catalysis B: Environmental, vol. 282, p. 119408, 2021

Efficient Reduction of CO_2 to fuels on oxide derived cupper electrodes and lateral surface structuring of photoelectrodes enhances alkaline water splitting

The electrochemical reduction of CO_2 (CO_2RR) provides an attractive means to synthesize fuels and feedstock chemicals in a sustainable way. However, large-scale utilization is still hampered by the low selectivity of most catalysts for many of the potential products as well as high overpotentials. So-called Cu oxide-derived (Cu-OD) Cu has been identified as a promising electrode material, overcoming part of these limitations. The catalytically active Cu-OD electrode is obtained operando from Cu_2O primary material at CO_2RR electrode potentials and exhibits a high selectivity for C_2 products, in particular for ethylene. Alternatively, it was considered to be inactive towards alcohol formation. The Krischer group has established a protocol for the generation of Cu-OD Cu electrodes that are highly selective for alcohol formation and yield current densities as high as 300 mA/cm^2 geometrical area at overpotentials as low as -0.7 V. As the inset in Fig. 6a shows, the electrodes have a fractal, cauliflower-like structure and a very large surface area. In the bar chart of Fig. 6a, the selectivity of this electrode for alcohols is highlighted. At such a low overpotential, this combined high selectivity and reactivity is so far unprecedented.

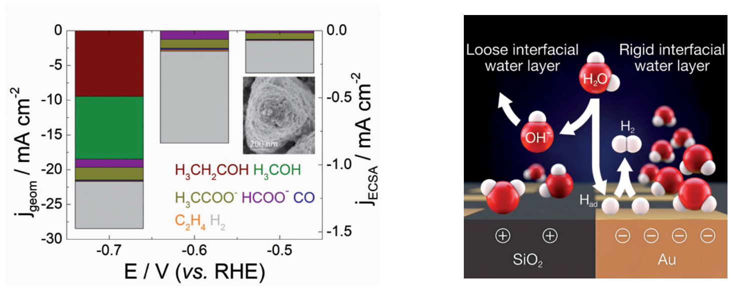


Fig. 6: a) The fractal-like electrode structure shown in the inset reduces CO_2 with high selectivity and high efficiency to ethanol and methanol at low electrode potential. b) At the Au/SiO_2 /electrolyte three phase boundary the structure of the water in the double layer is disturbed which enables a faster rate of hydrogen evolution in alkaline media.

Devices designed for solar-to-chemical energy conversion, where metals act as the (electro-)catalytic active material, need patterned interfaces in order to ensure a high absorption efficiency for solar light inside the device while enabling chemical transformation of species at the metal-based reaction sites at the interface. Furthermore, patterning saves expensive noble metal material. Besides that, the Krischer group discovered already that the patterning can have an enormous influence on the catalytic activity of the system. More precisely, silicon-based photoelectrodes decorated with a well-ordered array of gold structures have been investigated.

The gold array could be produced very cost-efficiently on a large scale with the method lift-off nanoimprint lithography. It has already been seen that the close vicinity between gold (catalytic active material) and the presumable catalytic-inactive support (silicon oxide) enhances water splitting in alkaline media tremendously. This enhancement has been attributed to a bifunctional mechanism, which appears at the boundary between the metal and the support (see Fig. 6b). This discovery can make a large contribution to the development of an efficient solar-to-hydrogen transformation device.

[14] T. L. Maier, M. Golibrzuch, S. Mendisch, W. Schindler, M. Becherer, and K. Krischer, “Lateral silicon oxide/gold interfaces enhance the rate of electrochemical hydrogen evolution reaction in alkaline media,” J. Chem. Phys., vol. 152, no. 15, p. 154705, 2020

Exploring functionality and stability of organic and perovskite solar cells on the way to novel application fields

The Müller-Buschbaum group researches functional materials and is specialized in relating material properties to their function in thin-film systems. Besides research on thermoelectrica, smart sensors, and battery electrode materials, the group focuses on next-generation organic and perovskite solar cells. These solar cells have gained increasing attention over the last few years due to the huge advances in material compositions and wet-film processing techniques. Thus, they will likely play an important role in sustaining the electric power of the future. The Müller-Buschbaum group employs advanced X-ray and neutron scattering for structure characterization combined with complementary analysis techniques to develop a comprehensive link between the layer deposition, layer morphology, and layer functionality.

For example, during the operation of printed organic solar cells, grazing-incidence small- and wide-angle X-ray scattering was used to study morphological degradation during solar cell aging in-operando [15]. By correlating the time evolution of the solar cell performance with the theoretical expectations based on modeling the X-ray scattering data (see Fig. 7a), morphological changes could be identified to cause solar cell aging seen in the performance decrease over time. Such studies help to reveal the mechanisms underlying solar cell aging, which in turn allows for material optimizations on the way to long-term stable next-generation solar cells.
In another work, perovskite and organic solar cells were launched on a sub-orbital rocket to space (see Fig. 7b) and measured during operation in orbital altitudes in a pioneering experiment [16]. To date, this is the first time that the next-generation solar cells in space in extreme environmental conditions are investigated. The different solar cell types survived the harsh conditions of the rocket launch and ascent. They showed promising power production exposed to bright solar irradiation as well as under faint-light conditions during the entire flight.

The Müller-Buschbaum group could prove that perovskite and organic solar cells can match their performance expectations and produce electric energy comparable to terrestrial applications. Next-generation thin-film solar cells are particularly interesting for space applications because the µm-thin modules can be deposited at low temperatures on ultra-thin plastic foils, potentially saving 90% of the module weight at the same power production compared to conventional solar cells. Moreover, these key features of flexibility and light-weightiness will help to establish the solar cells for various terrestrial applications in mobility and other energy-related fields towards a regenerative future.

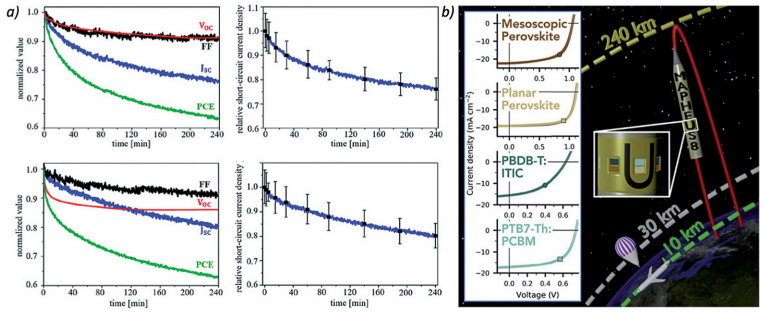


Fig. 7: a) Evolution of printed organic solar cell performance parameters over time, based on 1:1 (upper graphs) and 1:2 (lower graphs) donor:acceptor ratio of PBDB-T-SF:IT-4F. Comparison of the measured (blue) and predicted JSC (black dots) from modeling the solar cell film morphology with X-ray scattering data (right graphs).
b) Schematic overview of the experiment launching perovskite and organic solar cells to space. The inset shows that perovskite and organic solar cells match the performances obtained in terrestrial measurements and are therefore promising candidates for the application in space.

[15] K. S. Wienhold, W. Chen, S. Yin, R. Guo, M. Schwartzkopf, S. V. Roth, P. Müller-Buschbaum,“Following in Operando the Structure Evolution-Induced Degradation in Printed Organic Solar Cells with Nonfullerene Small Molecule Acceptor,” Sol. RRL, vol. 4, no. 9, p. 2000251, 2020

[16] L. K. Reb, M. Böhmer, B. Predeschly, S. Grott, C. L. Weindl, G. I. Ivandekic, R. Guo, C. Dreißigacker, R. Gernhäuser, A. Meyer, P. Müller-Buschbaum, “Perovskite and Organic Solar Cells on a Rocket Flight,” Joule, vol. 4, no. 9, pp. 1880–1892, 2020

Research activities Thermofluiddynamic (TFD) Group

The Polifke group researches thermofluid dynamics, specifically in the thermoacoustics field, tackling the problem of combustion instabilities in gas turbines, rocket motors, etc. that result from an interaction between acoustic fluctuations and unsteady heat release. In 2019, the POLKA (Pollution Know-how and Abatement) EU-project was established with objectives for decarbonization of energy production through the use of hydrogen in combustion devices. Three early-stage researchers (ESRs) of the network collaborate under the supervision of Prof. Polifke.

Using CFD and recently developed tools of Machine Learning, the research aims to firstly better understand flame-flow-acoustics interacting mechanisms and secondly to enhance the development of low-order-models for flame dynamics to be used in network models for stability predictions (schematic representation in Fig. 8a). Furthermore, in the context of using fuel blends with richer content of hydrogen, its influence on thermoacoustics features is currently explored. The first question is how the effects of hydrogen enrichment on the Flame Transfer Functions (FTF), representing the flame dynamics, could be predicted and easily “scaled” in order to retrieve known discovered behaviors of hydrocarbon

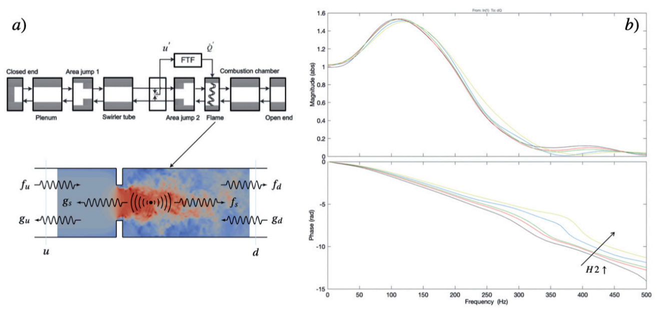


Fig. 8a): Sketch of acoustic network model.
b): Flame Transfer Functions (FTF) with increasing content of hydrogen,
Top: Gain – Bottom: Phase

flames. Recent advancements, exploring on the hydrogen faster consumption speed, have revealed that similarly stabilized flames respond quicker to velocity perturbations when the H_2 content is increased (shown in Fig. 8b). This is identified as a consequence of further increase of consumption speed due to the hydrogen flames' sensibility to stretch.

Another important part of the research is dedicated to compute high fidelity CFD simulations via LES approach in order to numerically reproduce recent experimental measurements of turbulent flames, clearly of higher interest for industrial applications. To this end, suitable models for turbulence and chemical kinetic are assessed for different methane-hydrogen mixtures. Here, the goal aims not only to detect the dominant flame dynamics effects but also to scale the relevant features in order to have unique FTFs, without performing computational expensive CFD simulations depending on the operating conditions.

An alternative study on thermoacoustics based on complex network approach is investigated. Here, the combustion flow field data is represented as a network structure consisting of nodes and links. A chemiluminescent intensity correlation network is constructed using a nonlinear correlation measure, namely so-called "mutual information". Recent findings have shown that with increasing instability, the network detects a build-up of spots of increased correlation and coherency around specific combustion chamber zones, i.e., the outer shear layer, together with a shift of the main information propagation direction from axial to radial. These observations indicate the critical regions for classification, prediction and suppression of instabilities.

Research activities at the chair of energy systems (LES)

The Spliethoff group's research is divided into four focus areas: 1) power generation and thermodynamic cylces, 2) solid fuel conversion, 3) energy storage and 4) power-to-X and reversible fuels cells. The group co-operates with fellow research institutions, as well as industrial companies, on several national and international research projects.

The Spliethoff group aims to demonstrate the technical operation of entrained flow gasification (EFG) with several different feedstock materials. A broad spectrum of feedstock is investigated ranging from pyrolysis coke including phosphorus recycling from sewage sludge to biomass residues and wastes [17]. The implementation of a polygeneration plant, where electricity and synthetic energy carriers can be flexibly produced from a solid fuel is investigated using experiments in lab- and pilot-scale test rigs. Computational fluid dynamic (CFD) simulations are employed to gain more of a detailed understanding of several EFG and gas cleaning processes [18]. The potential of such plants is identified by techno-economic calculations and energy system simulations. The technological combination of a biomass EFG and a continuous biological conversion of the synthesis gas to alcohols (BtL) with an optimized gas purification is developed in the course of the ReGasFerm project. The goal is the development of a gas purification system that is best suited for the coupling of gasification and gas fermentation. The coupling of a biomass gasifier with solid oxide fuel cells (SOFCs) to generate electricity from biogenic syngas at highest efficiencies is experimentally tested and systematic investigations of the material interactions are conducted in addition to electrochemical single cell degradation tests. With its Power-to-X (PtX) activities in the course of the projects e2Fuels and BioCORE, the Spliethoff group is also working to achieve long-term transformation solutions through sector coupling [19].

[17] T. Netter, S. Fendt, H. Spliethoff, "A collection of model parameters describing the gasification behavior of different fuels under entrained flow conditions". Fuel 296, 120536 (2021)

[18] R. Schwarz, S. DeYoung, H. Spliethoff, "Numerical simulation of gasification with a one-dimensional particle submodel for char structure evolution", Fuel 293, 120492 (2021)

[19] V. Dieterich, A. Buttler, A. Hanel, H. Spliethoff, S. Fendt, "Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review", Energy & Environmental Science 13 (10), 3207-3252 (2020)

Geothermal energy and system studies

Heating and cooling are responsible for almost half of EU's final energy demand. The goal of biomass-based technologies was to increase its share in the heat market in Europe from 11 % in 2007 to about 25 % in 2020. Within the Geothermal-Alliance Bavaria project, different aspects of geothermal heat utilization are researched by the Spliethoff group. The methodical analysis of operating data from existing geothermal heating plants has been used to develop monitoring tools for plant operators, including detailed component models [20]. The prediction of plant degradation by scaling and fouling and resulting smart and cost-efficient maintenance concepts can lead up to several hundred thousand euros per year in additional revenue for geothermal plant operators.

The construction and operation of an organic Rankine cycle (ORC) test rig (Fig. 9) allows for testing innovative process topologies for efficient combined heat and power (CHP) generation from geothermal sources. This includes turbine bleeding and direct contact de-superheating for more efficient condensation concepts [21]. The test rig is used to validate a semi-empiric model for twin-screw expanders and to investigate the potential benefits of a trilateral flash cycle (TFC). Operation of an ORC test rig with different novel refrigerants shows that the currently widespread working fluid R245fa can be replaced by more environmentally friendly substitutes without significantly decreasing the plant efficiency. It has been shown that innovative plant concepts such as the integration of geothermal heat in absorption heat pumps for cooling purposes allow the co-production of heat and power from petro-thermal sources using supercritical CO_2 within deep closed thermosiphon systems.

Through process simulation and optimization, the Spliethoff group works to define techno-economic boundary conditions and to identify the potential of investigated energy technologies. On behalf of BUND Naturschutz in Bayern e.V. the group and ZAE Bayern conducted a study on the possibilities of a 100% self-sustained energy supply of Bavaria in the sectors electricity, heat, and mobility. The study includes several scenarios for a renewable Bavarian energy system in 2040, considering local boundary conditions and local potentials [22].

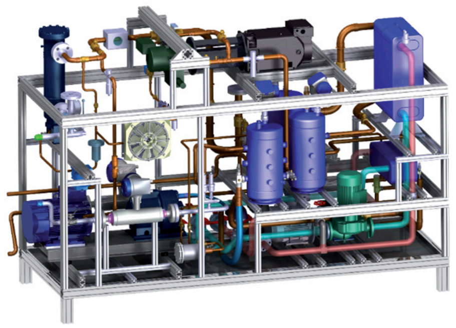


Fig. 9: ORC test rig without heat supply circuit

[20] M. Irl, J. Lambert, C. Wieland, H. Spliethoff, "Development of an operational planning tool for geothermal plants with heat and power production", Journal of Energy Resources Technology 142 (9) (2020).

[21] S. Eyerer, F. Dawo, C. Wieland, H. Spliethoff, "Advanced orc architecture for geothermal combined heat and power generation", Energy 205 (2020) 117967.

[22] Miehling, Schweiger, Wedel, Hanel, Schweiger, Schwermer, Blume, Spliethoff: "100 % erneuerbare Energien für Bayern. Potenziale und Strukturen einer Vollversorgung in den Sektoren Strom, Wärme und Mobilität." Garching bei München. 2021.

Network for Energy and Mobility Concepts

Head:

Prof. Dr. Constantinos Antoniou
c.antoniou@tum.de
Chair of Transportation Systems Engineering
Department of Civil, Geo and Environmental Engineering

Arcisstraße 21
80333 Munich
Tel.: +49 89 289 10460

www.tse.bgu.tum.de

is working on future mobility concepts, where innovative approaches are analyzed and disseminated. Mobility today is being disrupted by the so-called three revolutions: electric, shared and autonomous. Moreover, revolutionary concepts, such as hyperloop, are gaining traction and being discuss extensively.

The interdisciplinary nature of MSE places it ideally in the intersection of these three areas, as the collaborating chairs (Chair for Renewable and Sustainable Energy Systems/ Hamacher, Chair of Traffic Engineering and Control/Bogenberger, Chair of Transportation Systems Engineering/Antoniou) have established complementary expertise in these fields.

Current activities

The Network for Energy and Mobility is actively involved in several projects and activities within and outside MSE. Some project highlights are shown in the next sections of this paragraph.

SHARE-MORE: SHAREd MObility REwards mission

TUM Partner:

Chair of Transportation Systems Engineering (TSE)
Type: Innovation project
Funding: EIT Urban Mobility
Duration: 01/2020-12/2020

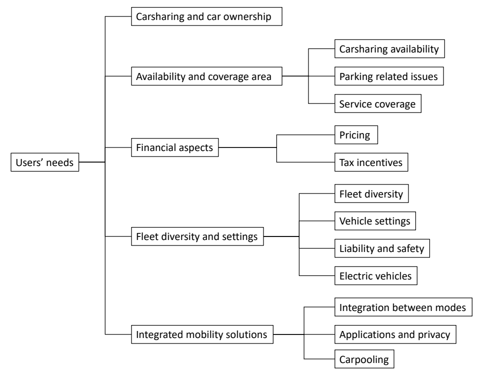
The overall objective of SHARE-MORE (SHAREd MObility REwards mission) is to optimize car-sharing services and promote a portfolio of transport modes that enable and encourage sustainable urban mobility. The project is part of the EITUM-2020 program, aimed to promote sustainable mobility solutions and reduce their environmental impact. The following partners take part in SHARE-MORE project: TUM (Chair of Transportation System Engineering, Prof. Antoniou), the City of Munich, the Technical University of Denmark, the City of Copenhagen, the Israel Institute of Technology, the City of Tel Aviv, and the University College London.

The effectiveness and sustainability of car-sharing integration into the bundle of transportation services is achieved in this project by understanding the needs of the three main stakeholders: travelers, transport authorities, and service providers, and by analyzing the need for personalized incentives tailored to the needs of all the three stakeholders. The incentives are explicitly designed to increase car-sharing efficient use while contributing to the integration with the existing transportation systems. An example of such incentives is an advanced booking option for recurrent trips to and from transport hubs for users whose travel patterns indicate activities matching such origins and destinations.

The project provides in-depth elicitation of car-sharing users' needs and provision of a list of potential user-directed and stakeholder-directed incentives that can be used to promote sustainable mobility and improve energy consumptions. This was achieved through two main steps:

- Qualitative studies: Exploratory focus groups and interviews with existing and potential future car-sharing users, service providers, and city officials from three cities of Tel Aviv, Munich, and Copenhagen. The identified key attributes from the focus groups and interviews discussions have been used as a basis to design and conduct a wider study.
- Quantitative studies: Based on the inputs from the qualitative studies, a travel survey was designed with the objective to collect qualitative data about individuals and household socio-economic characteristics, mobility tool ownership, travel patterns, and attitudes towards car-sharing, as well as stated preference data about willingness to use car-sharing. These data were used to quantify the potential benefit due to proposed (personalized) incentives.

The project identified thirteen potential areas of improvements where incentives can support car sharing. These are summarized into five main groups: carsharing and car ownership, availability and coverage area, financial aspects, fleet diversity and settings, and integrated mobility solutions. A more detailed report (available on https://eitum-sharemore.net.technion.ac.il/) provides guidelines on which actions and incentives should be used to achieve specific environmental and energy objectives.



Future Modular Battery Systems

Background

Project name:

Verkehr-SuTra: Technologies for sustainable transportation
Project ID: 57474280

Funding programme:
A New Passage to India
Deutsche-Indische Hochschulkooperation since 2019

Funding Agency: DAAD

Battery-driven Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are considered as a sustainable, pollution-free alternative compared to gasoline-driven cars, especially in the urban environment. The Indian Government has also introduced several schemes for promoting such green transportation solutions and it is aiming to convert almost 40% of its vehicle fleet into electric by the year 2030. However, introducing EVs in a mass scale is not straightforward, especially in the Indian context, due to the lack of proper charging infrastructure and the high cost, the limited driving range and prolonged charging time of these EVs. Batteries are the major component in EVs and HEVs, which also constitute roughly half of the overall vehicle cost. Moreover, the driving range and the charging times of an EV, which directly relates to the user acceptance of these new technologies, are also limited by the capability of the underlying battery pack. Therefore, for India to rapidly increase the number of EVs on road, smart technologies that can increase the range and enable faster charging at a reduced overall cost are imperative.

A high-power EV battery pack is typically formed using multiple individual Lithium-Ion (Li-Ion) cells that are connected in series and in parallel to achieve the required operating capacity. The cost breakdown of EV battery packs shows that apart from the raw materials cost to manufacture these Li-Ion cells, the major contributors are the yield of the manufacturing plant and the associated power electronics management systems required to operate these battery packs in the allowed safe region. With schemes like “Made In India”, the raw material cost of manufacturing EV battery packs could be greatly reduced. However, the focus now shifts towards improving the manufacturing yield and the system integration aspects of the battery packs that will significantly impact the overall cost of an EV. The design of existing battery management approaches is tightly coupled to the application in hand and is therefore not scalable for uses in different applications. For instance, the battery management approaches of an electric 2-wheeler or a 3-wheeler cannot be directly used for an EV or an electric bus, even though all of them use the same Li-Ion battery pack only having different number of cells in the pack. Here, new management systems, power electronics circuitry and control algorithms are required to be developed to increase the overall cost and time-to-market of an application. Moreover, the driving range and the charging time of an EV are determined by the differences between the capacities of the individual Li-Ion cells in the pack. In addition, the capacity variations also limit the manufacturing yield of a Li-Ion battery plant, since the automotive OEMs impose strict regulations in selecting cells with similar characteristics to form the battery pack and discard the cells that do not fall within the allowed threshold limits. Smart approaches that overcome the variations of the individual cells in the pack will increase the driving range, reduce the charging time and also minimize the overall cost of the EV by increasing the manufacturing yield.

Scalable, Low-cost, Modular Battery Systems

In this project, we overcome the above drawbacks by distributing the associated power electronics and the management modules to the individual cell-level, thereby decoupling the strong reliance of the management systems from the application. Here, each Li-Ion cell is associated with an intelligent controller that monitors and maintains the safe operation. In addition, the cell controllers are also equipped with a communication interface for interacting with other cell-level controllers in the pack. We call this combination of Li-Ion cell and the controller the smart cell. Consequently, a scalable battery pack can be formed in a plug-and-play fashion by interconnecting multiple smart Li-Ion cells, depending upon the energy and power requirements of the application. Using the concepts of distributed computing and self-organizing systems, the network of smart cells interacts with each other to form a fully functional battery pack, without the need for developing custom-designed supervisory management systems. This significantly reduces the overall cost of a Li-Ion battery pack by enabling interoperability and scalability since the same management and control approaches can be used for different battery-driven vehicles. Moreover, to minimize the capacity variations between the individual Li-Ion cells, we propose energy-efficient active cell balancing architectures that can redistribute the charge level among the cells in the pack. Active cell balancing improves the driving range and reduces the overall charging times by compensating the weakest cell with the energy stored in the other strong cells in the pack. This also improves the yield of the Li-Ion manufacturing plant by allowing the OEMs to select cells with larger variations, thereby reducing the overall cost of the Li-Ion battery pack.

Second-life Use of Battery Packs

Background

Global warming and associated climate change are considered a serious issue not only in developed countries like Germany, but also in emerging economies like India. The power and transportation sectors are identified as the major sources of CO_2 emissions and immediate steps are required in these domains for reducing the greenhouse gas levels. For this reason, the Government of India has planned to reduce the dependency on fossil-fuel based power generation and focussing on renewable energy sources such as solar, wind, hydro, etc. However, unlike many developed countries, India’s goal for reducing greenhouse gas emissions is not straightforward due to the huge population coupled with the immediate task of tackling widespread poverty. Moreover, the intermittent nature of renewable energy sources due to the dependence on environmental conditions challenges the stability of the power grid and results in a significant economic loss. For instance, The Comptroller and Auditor General (CAG) of India estimated approximately 2.4 billion INR losses due to lack of power evacuation from Tamil Nadu’s wind farms during the period 2007-2014. Even though stationary Electrical Energy Storage (EES) systems could be used to mitigate the uncertainty introduced by the renewable energy sources, they are expensive and are not attractive for emerging countries like India, where the priority is to support the rapid growth in GDP. Therefore, cost-effective and quick turnaround solutions for both renewable energy sources coupled with stationary EES systems have significant potential to solve India’s energy and pollution crises and support the country’s economic growth.

Low-cost EES and PV system

In this project, we propose a low-cost, scalable solution for forming a modular, integrated PV+EES system by reusing the retired modules from their first-life applications. A single module of our proposed PV+EES system could be appropriate in a single home and it is expandable to bigger setups, such as a village, by simply plugging in multiple similar modules. This will allow a system that smoothly scales over time without requiring any redesign or custom modifications, thereby minimizing the overall system integration efforts and cost. Further cost reduction is obtained by using retired modules, such as aged batteries from Electric Vehicles (EVs) and aged PV modules. Battery packs used in EVs must be replaced once their lifetime reaches 70% and currently these packs are recycled to obtain raw materials for manufacturing new batteries. With still 70% energy content available in these packs, they could be used in second-life for less demanding applications such as stationary EES systems, instead of wasting the remaining storage potential by recycling. Similar conditions exist for PV modules, where the aged modules are still capable of generating 70% power by harnessing the solar energy. However, the battery packs in current EVs are not designed to be directly reused in a second-life application. Battery packs from EVs of different manufacturers vary in size, capacity, electrochemistry, age, usage pattern and their associated control electronics, thereby challenging the task of interconnecting them to form a scalable PV+EES system.

We propose a cost-effective solution for integrating heterogeneous battery packs and PV modules from different manufacturers into a modular, scalable PV+EES system. Our proposed approach directly reuses the entire battery pack and its associated management system from the EV and interfaces with other packs from different manufacturers through an intermediate Battery Control Unit (BCU) that acts as an interface between the different management systems. Moreover, the electrical architecture is

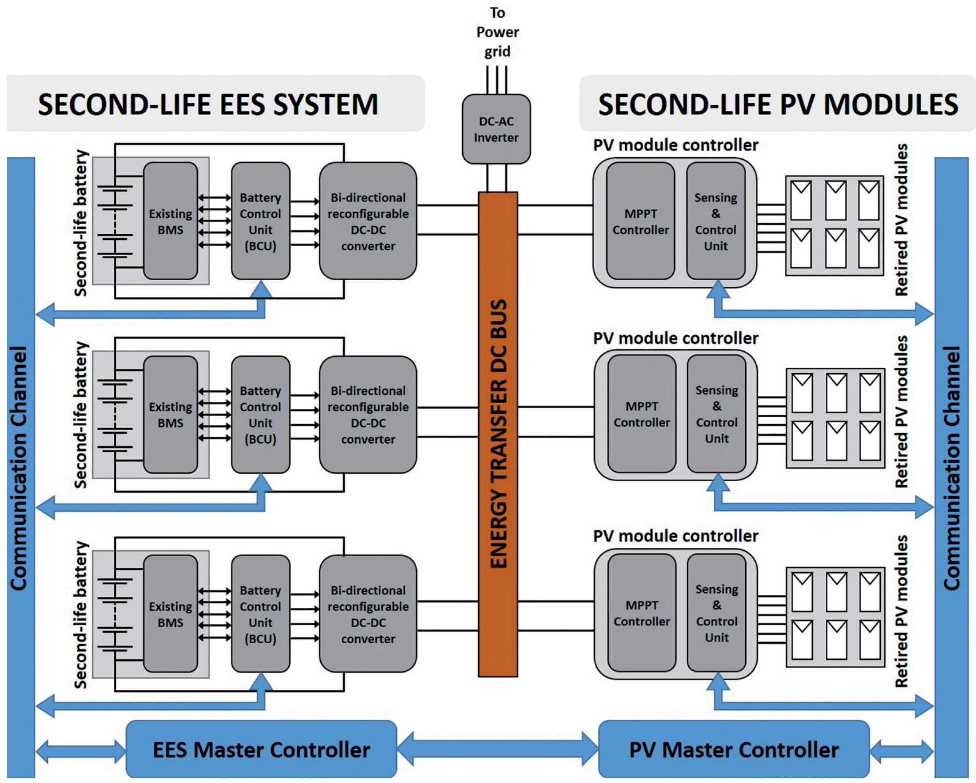


Fig. 1: PV+EES system architecture using heterogeneous retired PV modules and second-life battery packs from EVs

formed by interconnecting all the retired battery packs into a common DC bus through a DC-DC converter that can be directly interfaced to the electrical grid. Similar power electronic control units and management modules are used to interface heterogeneous PV modules to form a scalable PV+EES system. Using smart management algorithms, our proposed approach can optimally utilize the energy content of each battery pack in the EES based on its aging profile to maximize the lifetime and efficiency of the overall PV+EES system. Fig. 1 shows the overall system architecture of our proposed approach for building a scalable PV+EES system using retired modules.

TUM Hyperloop Program

TUM Partners:

TUM Department of Aerospace and Geodesy (LRG),
Munich School of Engineering (MSE),
Chair of Renewable and Sustainable Energy Systems (ENS),
Assistant Professorship of Sustainable Future Mobility (SFM),
Chair of Concrete Structures,
Chair of Carbon Composites (LCC)

Funding: Hightech Agenda Bayern of the Bavarian State Government

Hyperloop is an ultra-high-speed transportation concept published by Elon Musk in 2013. It consists of a low-pressure tube network, stretching over long distances and connecting mobility hubs and city centres to each other, and passenger or cargo vehicles, generally called pods, which travel contactless inside them at speeds approaching 1000 km/h thanks to the reduced air drag. Such a system would therefore combine the comfort of a train ride with the speed of an airliner flight, all while having no direct emissions and being energy efficient.

The publication of the hyperloop white paper quickly generated a growing interest in futuristic concepts for ultra-high-speed transportation systems. A considerable number of companies as well as student and research initiatives were founded all over the world to develop and implement the system. A further incentive was the announcement of the Hyperloop Pod Competition by Elon Musk's aerospace company SpaceX in 2015. Hundreds of teams registered for each of the four editions of the competition, which were held till 2019.

Following the very successful participation of the student team in the competition, the Technical University of Munich decided to launch a large interdisciplinary research program on this topic at its newly founded Department for Aerospace and Geodesy in 2020. This effort aims to develop the technology needed to make a climate-neutral, ground-based transportation system, based on the Hyperloop concept, a reality. Given the multidisciplinary nature of such a system, a considerable number of chairs and institutes at TUM are involved: the Munich School of Engineering, the Chair of Renewable and Sustainable Energy Systems (Prof. Hamacher), the Professorship of Sustainable Future Mobility (Prof. Jocher), the Chair of Concrete and Masonry Structures (Prof. Fischer) and the Chair of Carbon Composites (Prof. Drechsler).

In order to enable a thorough research of this ultra-high-speed transportation concept, two complementary research objectives are pursued in parallel within the TUM Hyperloop program:

- Full-Scale Demonstrator: A full-scale technology demonstrator will be developed and built between 2020 and 2022. The demonstrator will consist of a 24-meter vacuum tube and a matching human-sized pod.
  The technical implementation is crucial for the development of a future Hyperloop system. Integration and functional tests are to be carried out on the demonstrator in order to identify problems at an early stage and research solutions that are technically and economically feasible. In addition, experimental data will be collected this way, which can be used for concept analysis.

- Concept Analysis: Parallel to developing and testing the technology, models and analysis of the researched system and its large-scale implementation are necessary. With these tools, various concepts are investigated for technical and economic feasibility and the system's long-term capability is improved. In addition, potential security risks are analyzed and identified at an early stage and suitable measures are developed. Finally, these investigations should result in proposals for suitable implementation options in the existing transport infrastructure.

Fig. 2: A visualization of the hyperloop vision

Energy-Food-Water Nexus

Head:

Prof. Dr. Thomas Hamacher
thomas.hamacher@tum.de
Munich School of Engineering

Lichtenbergstr. 4a,
85748 Garching

Dr.-Ing. Petra Liedl
liedl@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a,
85748 Garching

at MSE explores the connected challenges of energy, food and water in times of urbanization, population rise and climate change. It unites competences ranging from innovative agriculture, lighting systems, sustainable building, energy systems and energy modeling with horticulture and indoor farming.

The participating institutes and chairs at TUM are namely Digital Agriculture (Prof. Senthold Asseng), Walter Schottky Institute (Prof. Martin Brandt), and Renewable and Sustainable Energy Systems (Prof. Thomas Hamacher). The “Energy-Food-Water Nexus” is linking MSE with the World Agricultural Systems Center (Prof. Senthold Asseng). Further partners of the network are the Applied Science Centre for Smart Indoor Farming at HSWT (Prof. Heike Mempel), Bright Box (Prof. Jasper den Besten), the Studentenwerk München in the area of Hochschulgastronomie (Ralf Daumann), the Competence Center for Nutrition in Bavaria (Christine Röger) and the Landesanstalt für Wein- und Gartenbau (Andreas Schmitt)

The network’s activities range from applied research to practical application.

Motivation for research

Sustainable food production will play an increasingly central role in the discussion concerning urban sustainability. Cities consume more than two thirds of the overall final energy and are responsible for more than 70% of CO_2-emissions worldwide. Therefore, cities can and should take a leading role for decarbonization by reducing their CO_2-emissions. Sustainable solutions in the areas of food, energy and transport as integral parts of cities are crucial to tackle the challenges of climate change.

Within the area of food production, technical measures such as protected cultivation are discussed in addition to an adaptation of crop management. Inner-urban and locally produced fresh products in vertical indoor farms are then the logical continuation of the technological progress. Vertical farming must be very productive to compete with conventional cultivation systems like greenhouses or outdoor cultivation. The optimization of the whole system is a technological task that can only be done with an interdisciplinary approach and experts in the respective disciplines.

Vertical farming has the potential to become a new and rapidly growing field of business activity for the building industry. The export of such systems to emerging countries could bring vertical farming to regions that are highly affected by climate change and whose citizens hardly have reliable access to fresh food. For industrial countries however, social aspects like the interaction between producer and consumer or the transfer of knowledge about nutrition are relevant.

Research scope

The food industry undergoes major changes, and this transformation process needs to face global challenges: climate change and weather extremes, food security, water demand, nitrogen input into nature as well as reliance on phosphate and fossil fuels or the competition between cities and agricultural land. For the nexus energy-water-food, energy demand is predicted to increase by 50% and similarly water demand by 30% in 2030. Discussions are underway regarding sustainable nutrition through innovative concepts and weather independent cultivation of products under optimal conditions for plants regarding illumination, temperature and CO_2 content. This cultivation method enables a high level of control on the product, but requires huge expertise to produce high quality while using resources most efficiently. In this context, vertical farming is defined as stacked levels for optimal usage of the floor area. The main advantages here are food security and environmental protection. However, vertical farming concepts are reviewed critically since the energy demand, costs for illumination and air conditioning cannot compete with outdoor cultivation or greenhouses for the time being.

Therefore, the network has devoted its mission to approach the central research question, whether vertical farming has the potential to become a sustainable system for urban food production and an enabler to future agriculture. The specific topics comprise:

- Developing building concepts for vertical farming, which are energetically optimized, but also economically attractive
- Integrated modeling of thermodynamic processes at plant level and the interaction with artificial illumination
- Integrating vertical farming into an extended energy system of a heterogeneous structure such as a campus or an urban quarter
- Implementing a life-cycle-analysis optimization for vertical farming as a whole system

Current and future activities

Vertical Farming Box

Prof. Dr. Thomas Hamacher, Heinrich Kleeberger
Chair for Renewable and Sustainable Energy Systems
Lichtenbergstr. 4a
85748 Garching

The Chair for Sustainable and Renewable Energy Systems developed a prototype for a vertical farming box. The highly flexible, low-cost and remotely controlled box measures 0,85m x 0,85m x 1,85m and features a high flexibility for demonstration purposes. It provides constant water flow (ebb-and-flow-system) featuring controllable conditions including illumination (water-cooled LED lamps), temperature, humidity and air circulation. With this small- scale unit, researchers and students have a valuable tool to explore the interaction between the walls, the plants, illumination (color, intensity, control, distribution) and ventilation. In workshops students have been keen on further developing the box by adding sensors and assessing operational data.

Heinrich Kleeberger / TUM

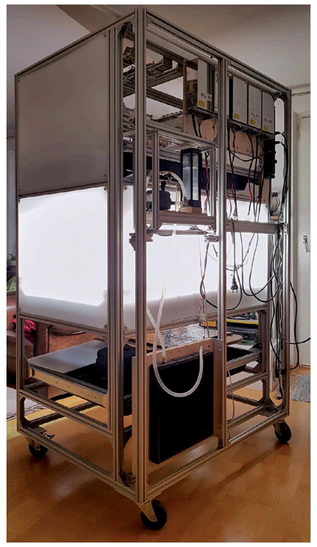


Fig. 1: Vertical Farming Box

Vertical farming goes to Garching

In cooperation with:
Ralf Daumann
Studentenwerk München,
Hochschulgastronomie
Leopoldstraße 15
80802 München

A potential assessment developed by MSE explored the implementation of a vertical farm next to the new cafeteria at TUM campus Garching. Usually between 4.000 and 5.000 meals are produced daily in the canteen, which offers seating for 1.750 visitors and 7.000 meals in a very narrow time slot of a couple of hours on a 5.300 m² floor space. The three-storey vertical farm with a ground floor area of just 82 m² and a cultivation area of 351 m² would provide space to produce about 75 kg of salads and herbs per day for the close-by canteen. Some of the many benefits that a vertical farm would bring to the campus include the fresh and all year-round production close to the consumers, the reduction of goods transportation, the use of a very small foot-print while still having an increased productivity and at the same time decreasing the use of fertilizers and herbicides.

Petra Liedl and Fernandina Valdebenito / TUM

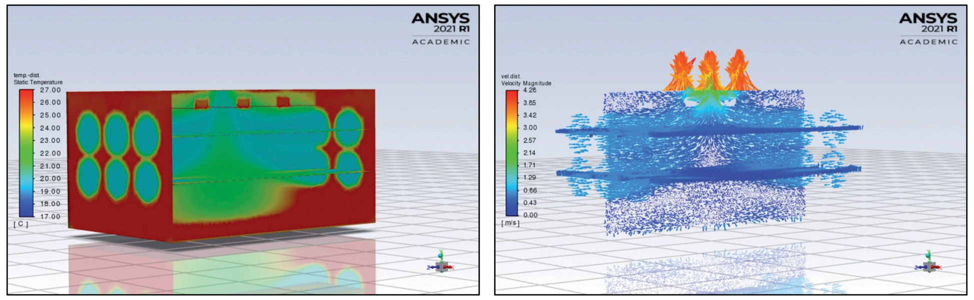
Fig. 2: Vertical farm next to the new cafeteria at TUM campus in Garching (Rendering)

OpEn Farming

The goal of the project "OpEn Farming: Holistic optimization of the energy system vertical farming by integration into a cycle economy" is to energetically optimize vertical farming as a whole by identifying synergies between the parameters lighting, temperature, ventilation, water, nutrients and plant growth.

Between 2021 and 2023, MSE's project leader Dr. Petra Liedl will partner with the Chair for Renewable and Sustainable energy systems (Prof. Hamacher), the Applied Science Center for Smart Indoor Farming at HSWT (Prof. Mempel) and BrightBox in Venlo (Prof. den Besten) as well as with Precede Farm (Vivek Jadhav) in Singapore. The project consortium provides the opportunity to validate the simulation results with real data from the indoor farms in Weihenstephan, Venlo and Singapore.

This research project will be funded by the research initiative "Future of Building" ("Zukunft Bau") of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR).



Nader Faza / TUM

Fig. 3: Fluid simulations with software ANSYS to optimize ventilation within the vertical farming box (described above)

From Cartower to Greentower

A former full automatized Cartower that was run for a decade by Wohnungsbau Aalen has the potential to become a Greentower, both from the outside and the inside. Instead of cars, 24 modular containers with space for growing salads, herbs and vegetables could be stacked within the 12 levels. The fresh produced food could be distributed to local markets or inhabitants of the apartments of the Wohnungsbau on a daily basis. Together with Prof. Mempel and her team from the ASC at HSWT, MSE will conduct a potential study to convert the tower into a lighthouse project for the conversion of abandoned structures into vertical farms.

Petra Liedl / TUM

Fig. 4: Cartower with 12 levels for 2 cars each which could be converted to a Greentower with containers for vertical farming.

Winter Schools

Two winter schools about the Energy-Food Nexus were organized by the Graduate Center of the Munich School of Engineering in 2019 and 2020 for capacity built-up and networking activities. Further reading can be found at pp. 84 and 85.

Partner institutions

Prof. Dr Heike Mempel
Greenhouse technology, maintaining post-harvest quality, heating technology
Hochschule Weihenstephan-Triesdorf
Am Staudengarten 10,
85354 Freising

First-ever Applied Science Centre for Smart Indoor Farming at the University of Applied Science Weihenstephan-Triesdorf

The objective of the Applied Science Centre (ACS) with its director Prof. Heike Mempel is to establish an infrastructure within the indoor farming sector that serves as an interface between research and industry. Scientific questions are linked with specific application cases, while interdisciplinary projects play a crucial role in making this innovative technology ready to put into practice. In the spotlight are several innovative fields of application for indoor farming. These include the urban production of fresh plant foods, the production of raw materials for the food and pharmaceutical industries, and farming in poor climates (e.g. arid regions, contaminated land). The technology is extremely water-efficient, meaning it offers major potential in particular for regions with low water availability. A further aim of the centre is to develop energy supply concepts with the ultimate goal of achieving climate-neutral production in the indoor farm. In addition to this, the initiative seeks to optimize existing supply chains in order to make full use of the potential offered by indoor farming.

HSWT

Fig. 4: Indoor Vertical Farming Container with two separate growth units, several available cultivation systems, spectral compositions and light intensities.

World Agricultural Systems Center – Hans Eisenmann-Forum for Agricultural Sciences at TUM

Prof. Dr. Senthold Asseng
Claudia Luksch
Hans Eisenmann-Forum for Agricultural Sciences
Liesel-Beckmann-Str. 2
85354 Freising

At the Hans Eisenmann-Forum (HEF) Vertical Farming is one of the focus topics. HEF networks the agricultural research groups TUM internally and with external partners, initiates and coordinates research projects, and organizes the dialogue with stakeholders from society, practice, business and politics, and facilitates knowledge transfer with various events like lecture series and symposia. Together with the Chair of Digital Agriculture experiments on Indoor Wheat are carried out at the Gewächshausversuchszentrum in Dürnast at the Weihenstephan campus.

Digital Agriculture goes Wheat

Prof. Dr. Senthold Asseng
Chair for Digital Agriculture
Liesel-Beckmann-Str. 2
85354 Freising

The Chair of Digital Agriculture, Prof. Senthold Asseng, is engaged in simulation models of plant stands to improve plant system understanding and its control and optimization. Simulation models of crop stands are developed, tested and applied in the areas of: climate impact research, yield prediction, sustainability, farm robotics and indoor vertical farming.

ediundsepp

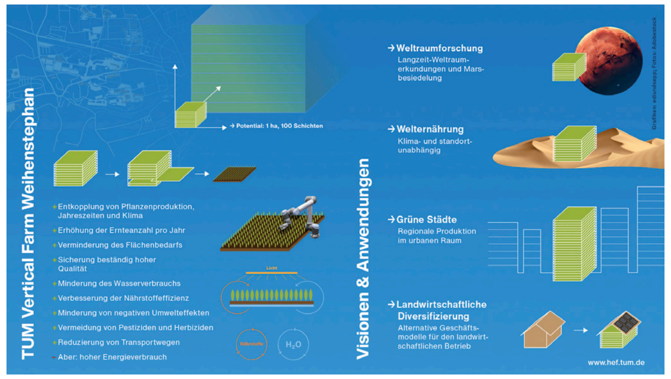


Fig. 5: Vertical Farm Weihenstephan

Claudia Luksch / TUM

Fig. 6: Indoor Wheat in Weihenstephan

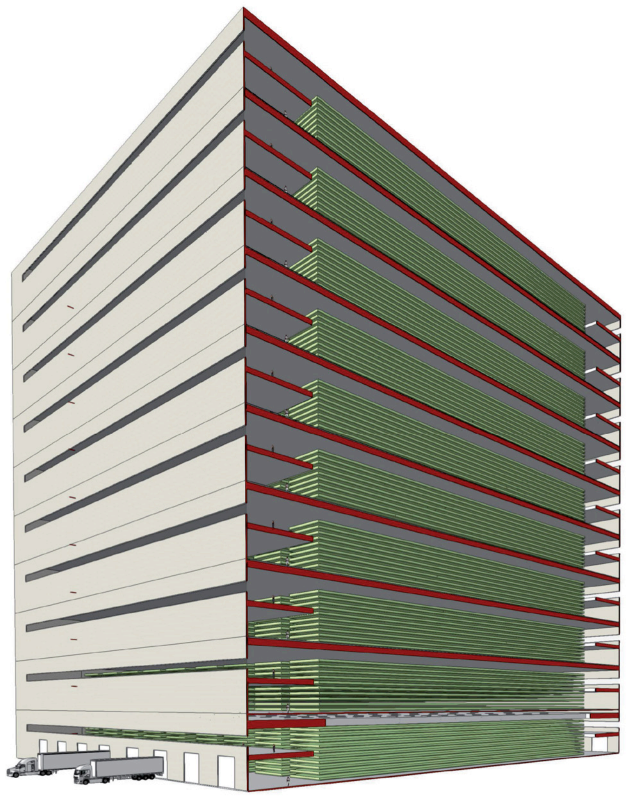


Fig. 7: Drawing of a multiple 1ha, 10-layer indoor vertical wheat growing

Wheat yield potential in controlled-environment vertical farms.
Senthold Asseng et al., PNAS August 11, 2020 117 (32) 19131-19135

BrightBox – So open, so inspiring

Prof. Jasper den Besten

BrightBox Venlo
St. Jansweg 15
5928 RC Venlo, Netherlands

BrightBox is Europe's unique expertise centre for daylight-free multi-layer cultivation, like city farming. By determining the ideal growing formula for a plant with light, air, temperature, nutrition, water and substrate, the team achieves the best results for the client. This means higher yields, lower cost price, faster production, better quality and more delicious flavor. The team lead by Prof. Jasper den Besten conducts research, produces, teaches and shares its knowledge.

Pim Vingerhoets

■ **Bright Box**

Competence Center for Nutrition – KErn

Christine Röger

Competence Center for Nutrition (KErn)
Am Gereuth 4,
85354 Freising

The Competence Center for Nutrition belongs to the Bavarian State Ministry of Food, Agriculture and Forestry. KErn has the objective to accelerate exchange between research, food industry/production, and nutrition education and to therefore facilitate the flow of information between all participating groups and to help transferring current knowledge into practice. KErn comprises three departments – Science, Nutrition information and Knowledge Transfer, and Food Industry and Production – and has offices in Kulmbach and Freising.

LWG, Bavarian State Institute for Viticulture and Horticulture

Andreas Schmitt

Bavarian State Institute for Viticulture and Horticulture (LWG)
Institute for Commercial and Recreation Holticulture
Galgenfuhr 21,
96050 Bamberg

The Bavarian State Institute for Viticulture and Horticulture is an independent regional authority within the Bavarian Ministry of Food, Agricutlure and Forestry. The working group Environmentally Friendly Production from the Institute for Commercial and Recreation Horticulture deals with questions around sustainable production with a focus in horticulture. Tests about ecological and conventional, here soil-independent, are carried out in the pilot farm in Bamberg, Franconia.

Andreas Schmitt / LWG

■ **Fig. 10: Testing basil regarding the exposure to light: LEDs compared to sodium vapour lamps**

Center for Combined Smart Energy Systems (CoSES)

Head:

Prof. Dr. Thomas Hamacher
Thomas.hamacher@tum.de
Munich School of Engineering

Dr. Vedran Peric
vedran.peric@tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52720

www.mse.tum.de/coses

The Center for Combined Smart Energy Systems (CoSES) is the central platform for joint research on smart renewable energy systems at TUM. The integrated approach is reflected by the co-operation of different institutes coordinated by the Director of the Munich School of Engineering, Prof. Hamacher. The scientific objective is an improved and increased integration of renewable energy resources in the energy supply of buildings on a local scale. Therefore, methods for influencing demand patterns, using energy storage opportunities and sector coupling are investigated. Final energy demands include heating, cooling and electricity also influenced by electric mobility. The interaction between systems and buildings, their communication and control are investigated by applying state of the art approaches of digitalization.

Motivation for research

The transition to more climate friendly energy systems imposed significant changes in their planning and operation [1]. These changes are characterized by intensive exploitation of renewable energy sources, such as solar and wind, and more efficient operation of the system by using Information and Communication Technology (ICT) systems. Exploiting the fact that electricity can be easily converted to different forms of energies and taking the trend of extensive electrification of heating, cooling and transportation sectors into account, the energy systems will feature wider adoption of micro CHP systems, heat pumps and electric vehicles. The power system will play a crucial role as the backbone of these future integrated energy systems. These changes have brought about a paradigm shift in the power system operation. At the same time, it also imposed several challenges on power systems to be researched, such as the analysis of dynamic behavior in low inertia systems, undispatchable and uncertain power production, unpredictable power flows, etc. The distribution systems, which are traditionally designed as passive radial grids, have to be restructured to account for the new concept of prosumers and bidirectional flows. This has led to the introduction of the microgrid concept, which assumes controllable entities that are able to reliably supply power to consumers even without connection to the superior transmission and distribution grid.

Even though the microgrid concept has been extensively investigated in the literature, the research topics are mainly focused on pure electrical systems, while the significant impact of the other energy sectors has so far been neglected. To address this gap, the CoSES at TUM has been established with a laboratory facility that can emulate a small microgrid combining heating, cooling, energy distribution and electric subsystems. With the aim to provide a test environment with conditions as close as possible to reality, the laboratory is equipped with the full set of high-power components that practically eliminate the need for modeling tools such as real-time simulators.

Stefan Hobmaier / TUM

The CoSES laboratory

The CoSES laboratory emulates a small microgrid that consists of five buildings/houses of different sizes with fully controllable electric and heat demand including distributed electric and heat energy generation [2]. These buildings are connected with a flexible electricity and heating grid. The main features of the experimental set-up as shown in Fig. 1 are:

- Electricity layer comprising (i) flexible electric grid that consists of an experimental and a feedback grid as well as (ii) distributed generation assets, (iii) battery energy storages and (iv) consumers on the domestic level, including EV charging stations
- Heat layer comprising a bidirectional 3-line district heating/cooling grid, including domestic heat prosumers with distributed heat sources (heat pumps, CHPs, solar thermal);
- Communication layer with flexible and seamless information and control technologies (ICT) for control and monitoring purposes

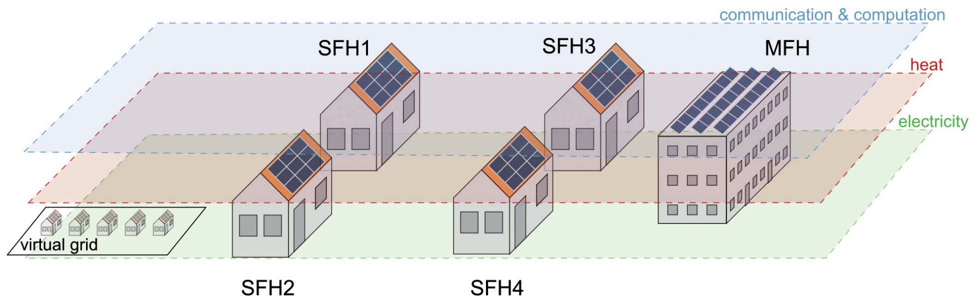


Fig. 1: Laboratory Overview

Electric System

A single line diagram of the default configuration of the experimental microgrid is shown in Fig. 2.

The medium voltage (20 kV) feeder supplies the experimental microgrid system. Two On Load Tap Changer (OLTC) transformers (250 KVA each) are supplying the laboratory experimental grid that consists of maximum ten low voltage (LV) buses. The topology of the LV grid is created by connecting these ten LV buses with twelve long distance cables that are integrated in the foundations of the building. The total length of all cables is around 1.8 km, with individual lengths between 100 m and 250 m and conductor (copper) diameter between 70 and 150 mm^2. The cables are accessible at the switchboard, where they can be connected to any of the ten LV buses, which allows for the realization of a flexible microgrid topology.

In addition to the flexible grid topology, several electrical components are available in the laboratory, which can be connected to any of the ten LV buses:

- Electric Batteries (2 x 13 kWh, extension planned with additional 100 kWh)
- Photovoltaic panels (18 kW_p). These solar panels are mounted on the ZEI roof.
- Synchrounous and induction motor/generator emulator (30 kW each). This is achieved by the motor/generator block, where the motor is controlled by an industrial inverter and provides desired torque to the experimental machine.
- 2 x EV charging station. EV charging stations are located at the parking lot in front of the building.
- Prototype of a 4 leg inverter (under construction)
- Egston prosumer emulator

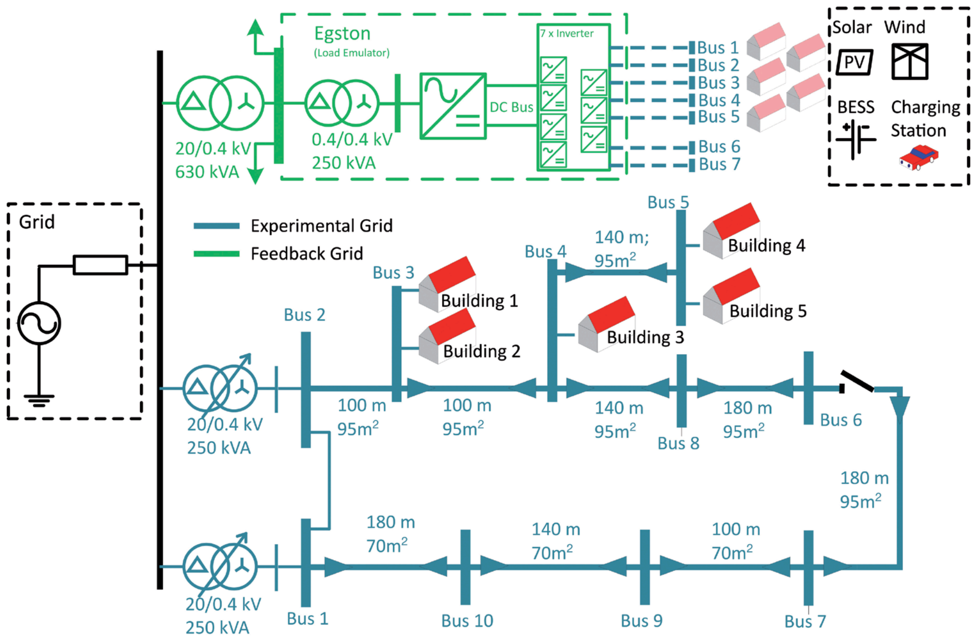


Fig. 2 Electric Grid Single Line Diagram

Stefan Hobmaier / TUM

Fig. 3 Photos of the laboratory equipment. a) Egston load emulator; b) solar panels; c) EV charging stations

The Egston load emulator consists of a transformer (galvanic isolation), rectifier, DC bus and seven three phase bipolar inverters connected to the common DC bus. A bipolar inverter represents a fully controllable load/generation with the maximum current of 126 A and voltage of 433 V. Five out of seven inverters are dedicated to mimic building prosumers. The other two inverters are used as additional load/generation that can be connected to an arbitrary LV bus, which is normally used to emulate additional renewable resources located outside of buildings.

The concept of circulating power flows is accomplished through a feedback grid that is supplied through the 630 kVA transformer. The feedback grid supplies the Egston load emulator and auxiliary equipment that is not part of the experimental grid.

As mentioned above, the experimental system consists of five buildings and the grid that connects them. Each of these buildings is emulated as a composite load through parallel connection of Egston inverter, solar panel, battery and several electricity outlets that can supply arbitrary household appliances as shown in Fig. 4.

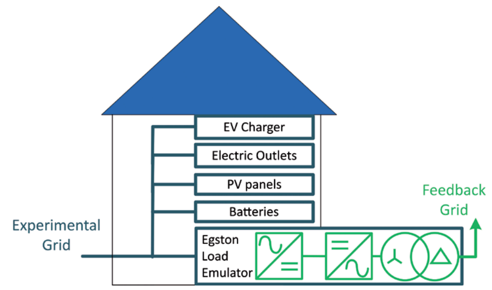


Fig. 4 Electric System of a Building

Heat System

A two and three-temperature-level bidirectional heating grid connects the five buildings, where each of the buildings is capable of taking the role of heat sink or source, i.e. to behave as a heat energy prosumer. Three buildings are connected by a three-temperature-level heat grid that provides enough flexibility to emulate heating and cooling systems or to supply heating at two different temperature levels.

The basic heating grid topology is shown in Fig. 5 and offers the possibility of reconfiguration with small efforts to also allow for a flexible topology on the heating side.

To avoid long piping infrastructure, special modules are inserted to emulate dynamic behavior and heat losses of arbitrarily long pipes. These modules introduce controlled delay in the hot water flow, which is accomplished with appropriate cooling or heating of the flowing water (depending on the heat flow change).

The buildings are equipped with different heating modules that enable various experiments with the heating system. The overview of the equipment is given in Table 1, whereas the principal scheme of the building's heating system, impressions of the heat modules and the CHP are given in Fig. 5 and 6.

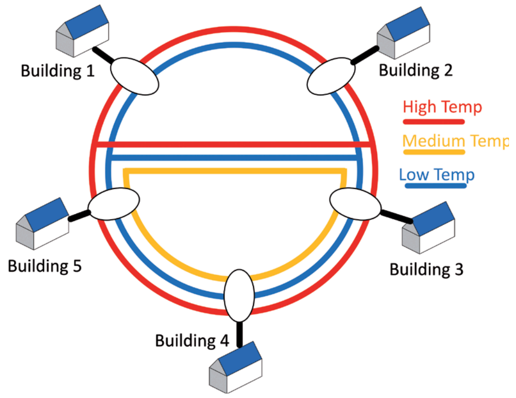


Fig. 5 Emulated heat grid with two and three temperature levels

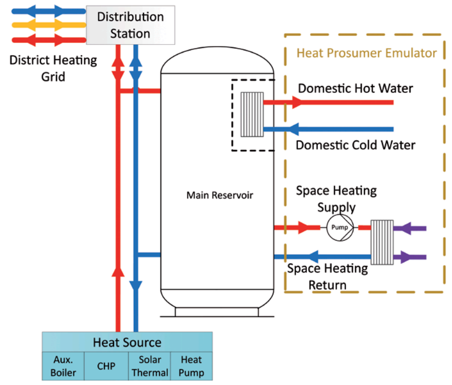


Fig. 6 Emulated heat system of a building

The central component in the buidling's heating system is the hot water storage, which can be heated from different sources (District Heating Grid, Heat Pumps, Boilers, Solar Thermal Sources or CHPs). The clean domestic hot water is supplied by an additional heat exchanger with optional storage. The amount of consumed hot domestic water is controlled through the valves, after which the water is tapped. The space heating consumption is emulated through the controlled heat exchangers, cooling the hot water to the necessary extent replicating the user profile. This emulated heat sink (space heating emulator) is determined through the simulation of the building's heating dynamics/heat balance. The building model is developed using Modelica language in SimulationX and its Green City library.

Stefan Hobmaier / TUM

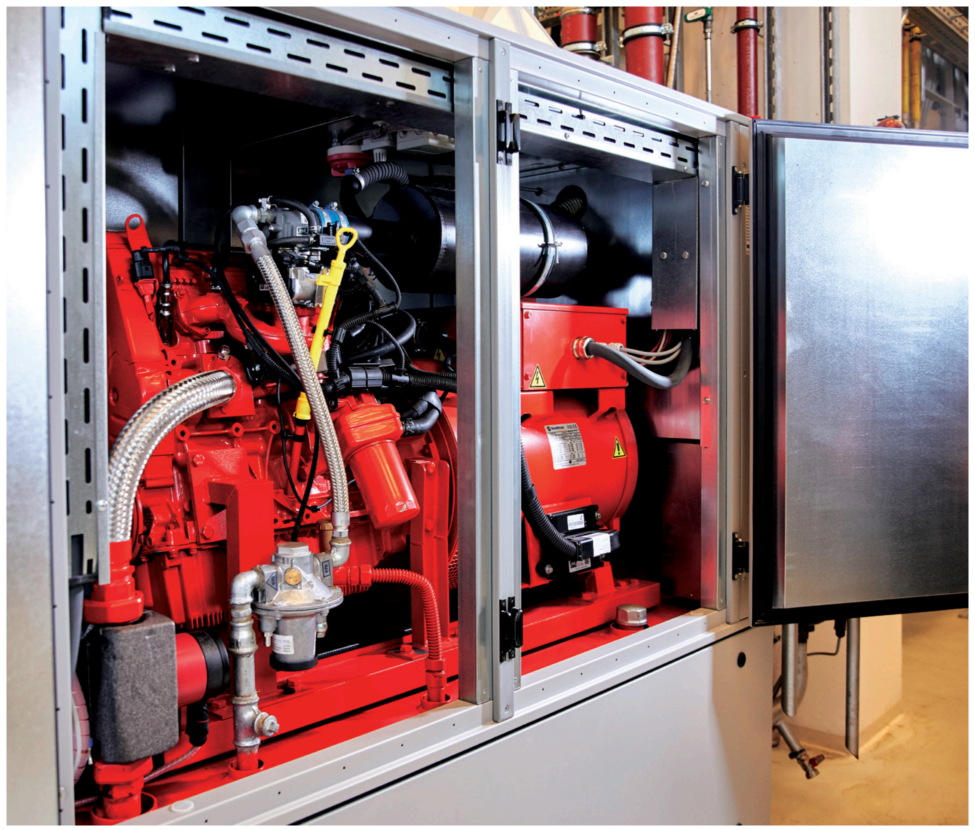


Fig. 8: 8 CHP of Building 5

	Building 1	Building 2	Building 3	Building 4	Building 5
CHP	Gas 2kW$_{el}$, 5,2kW$_{th}$	None	None	Stirling engine, 1kW$_{el}$, 6kW$_{th}$	Gas 5kW$_{el}$, 11,9kW$_{th}$
Gas 18kWel, 34kWth					
Aux. Boiler	Condensing boiler, 20kW$_{th}$	Condensing boiler, 20kW$_{th}$	None	Integrated in the CHP, 20kW$_{th}$	Condensing boiler, 50kWth
Heat Pump	None	Air source HP, 10kW$_{th}$	Brine source HP, 10kW$_{th}$	-----	-----
Solar thermal source (el. heater)	9 kW$_{th}$	9 kW$_{th}$	9 kW$_{th}$	-----	-----
Hot water storage	800 liters	800 liters	1'000 liters	1'000 liters	2'000 liters
Domestic Hot Water	Storage: 500 l	Fresh water station	Fresh water station	Combined storage	Fresh water station
Heat Sink	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	60 kW$_{th}$
Distribution Unit	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	30 kW$_{th}$	60 kW$_{th}$
Booster Heat Pump Distribution Unit	19 kW heat				
14 kW cold	–	–	–	–	–

Table 1: Overview of heat modules

Monitoring and Control System

The equipment described in the previous paragraphs represents the core of the laboratory design. The controlling and monitoring system allows for flexible and efficient utilization, which is essential for a successful research platform.

The lab's controlling and monitoring system is based on the National Instruments PXI systems and VeriStand software for building and deploying Software-in-the-Loop (SIL), Model-In-the-Loop (MIL) and Hardware-In-the-Loop (HIL) solutions. The controlling and monitoring architecture is shown in Fig. 9. Three workstations with NI VeriStand software are available for controller programming and adjustments in the system. It is important to note that it is not necessary to run lab experiments on the full system. Instead, a subset of the available controllers (and associated hardware) can be used independently from the remaining system at any time.

Each building and the microgrid control center have two controllers, one NI PXIe 8880 for electric systems, and one industrial controller NI IC 3171. These controllers operate extremely fast at a rate of 10 kHz and 1 kHz, respectively. The communication layer consists of a ring that operates at a 1 kHz rate. Reflective memory technology

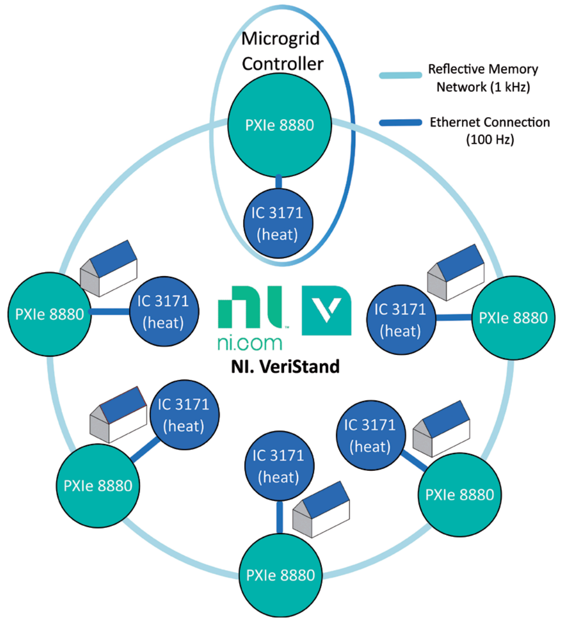


Fig. 9 Control and Monitoring Architecture

is employed for linking the real-time targets using the GE 5565 reflective memory cards. This ensures that all measured data is available to each controller. The industrial controllers communicate with corresponding PXIe systems through Ethernet cables at a 100 Hz rate.

In addition to playing the role of controllers in the experimental microgrid, NI PXIe systems are powerful enough to operate as a real time simulator, enabling the above mentioned SIL, MIL and HIL experiments. Once the solution is tested with simulated models, it can be validated in the Hardware-In-the-Loop or Physical Test configuration.

NI VeriStand software, which implements the V-Model of development, enables seamless transition from the simulation to fully hardware environment. This is accomplished through the standardized NI VeriStand interface (signals) between different models, which replicate the real-life interfaces. Therefore, if the simulation-model interfaces are defined to correspond to the hardware interfaces (control inputs, measured signals, etc.), the transition to the physical test configuration demands simply a reassignment of the interfaces to the real-life signals to the input and output interfaces.

NI VeriStand is able to load any compiled models, which enables the use of different modelling and development tools, such as MATLAB®, Simulink, LabVIEW, and .NET languages. In addition, NI VeriStand can be controlled through the NI VeriStand .NET API.

Research Scope

Multi-Energy Market Design

Sector coupling and optimal integration of renewable energy resources in the integrated Multi-Energy System require a complete paradigm shift of the system operation [3]. The challenge is to transform the existing individual sector business models and adapt them to the open multi-energy market environment while maintaining economic stability. The critical question for this new market environment is the management of the flexibility required to balance intermittent renewable energy sources. It is expected that sector coupling will play a major role for increasing system flexibility through efficient electricity based energy conversion. However, there are several research aspects that deserve an explanation:

One focus topic is the analysis, categorization and quantification of different flexibility options. The variety of resources that can contribute flexibility in power systems is broad and can be categorized as: (i) storage devices, (ii) conversion technologies and (iii) supply/demand-side management. Another approach is to categorize flexibility resources by their time scale in terms of impact and response time. They range from (a) long-term measures (e.g. transmission system expansion) over (b) mid-term resources (e.g. energy storage systems) to (c) short-term (e.g. demand response) and (d) super short-term resources (e.g. voltage control). These different types of flexibilities should have specific metrics that will provide the methods for optimal use of flexibility in a technology-agnostic way.

Further, the new business models will also have an impact on long-term system planning. The new systems should be planned holistically considering all energy sectors while respecting financial interests of the stakeholders. Finally, all these aspects should be used in defining an appropriate market design for energy but also for flexibility, while ensuring a stable investment in long-term infrastructure. These market mechanisms can have different time horizons: From intraday auctions continuously increasing to year ahead planning. Further, the markets can be based either on nodal or zonal pricing, which are schemes that all have their advantages and disadvantages.

Steady state optimization

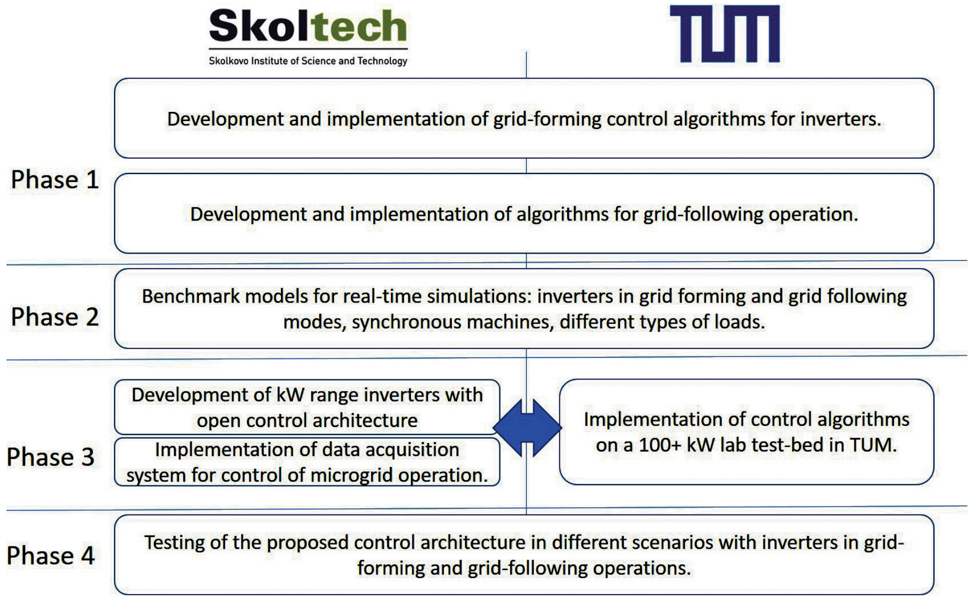
The optimal operation of the multi-energy system depends on the accurate monitoring and state estimation of the system [4],[5]. This aspect is often referred to as situational awareness, which is ensured through state-of-the-art monitoring system that collects various measurements from the system. These measurements are processed in the state estimation algorithms, using the accurate representation of the current system state that is continuously determined. The concept of a digital twin is widely used here, since it provides the possibility of virtual operation of the system where different control strategies can be assessed before being applied in the real system. A digital twin with advanced optimization techniques enables predictive optimization of the system that ensures the lowest possible operational costs while respecting all existing operational constrains. Solutions that optimize the system and provide situational awareness are referred to as energy management systems, which can further be divided in transmission system optimization, distribution system optimization or building/consumer system optimization.

Dynamic modeling and control

The accurate operation of multi-energy systems can be accomplished only when the dynamic aspects of multi-energy grids are well understood and controlled [6],[7],[8]. The dynamic analysis requires detailed modeling approaches based on differential equations. These models are then used for development of advanced control strategies that ensure the stability of the system. The phenomena of interest are frequency stability, power electronics interfaces, thermal and hydraulics dynamics and their interaction with the electric system. Decentralized control approaches in multi-energy microgrids are of special interest, since modern power-electronics-dominated microgrids are introducing several challenges related to decreased level of system inertia that traditionally helped in maintaining the system stability. New control approaches for zero-inertia systems are being developed that are characterized by fast responses and state-of-the-art information and communication infrastructure.

Control of Power Electronics Dominated Microgrids

The project has been initiated within the strategic partnership between TUM and Skoltech aiming at the build-up of capacities on both sides and to exchange relevant experiences. The project is motivated by the fact that power electronics devices have become much more affordable in the last few years, which resulted in unprecedented growth in the distributed generation, including renewables, most of which is connected to conventional power systems through inverters. Despite the considerable share of renewables (and its distributed generation) in the total power and energy balance, most of them are still connected to power grids using simple grid-following approaches, where inverters simply follow the grid frequency and phase, and supply the required amount of power. Such an approach, although suitable for grids with a low share of distributed generation, will become infeasible for grids with high shares of distributed generation or island-mode microgrids. Therefore, it is necessary to develop new approaches for control of power electronics and interfaced sources that can be universally used for grids with high penetration of renewable/distributed generation. In the proposed project we develop a number of control architectures to ensure stable and reliable operation of future power systems with high level of decentralization and high penetration of renewables.



References

[1] Thomas Hamacher, Vedran Perić, Philipp Kuhn, “Dialog der Systeme”, Forschung-Das Magazin der DFG, 1/2021.

[2] Vedran S Perić, Thomas Hamacher, Anurag Mohapatra, Franz Christange, Daniel Zinsmeister, Peter Tzscheutschler, Ulrich Wagner, Christian Aigner, Rolf Witzmann, „CoSES Laboratory for Combined Energy Systems At TU Munich“, IEEE PES General Meeting 2020.

[3] Verena Kleinschmidt, Thomas Hamacher, Mohammad Reza Hesamzadeh, Vedran S. Perić, „Unlocking Flexibility in Multi-Energy Systems: A Literature Review“, 17th International Conference on the European Energy Market (EEM), 2020. (virtual)

[4] Thomas Licklederer, Thomas Hamacher, Michael Kramer, Vedran S. Perić, “Thermohydraulic model of Smart Thermal Grids with bidirectional power flow between prosumers”, Energy, Volume 230, 2021.

[5] A Behzadi, A Arabkoohsar, VS Perić “Innovative hybrid solar-waste designs for cogeneration of heat and power, an effort for achieving maximum efficiency and renewable integration” Applied Thermal Engineering, 190, 2021.

[6] T. Kamal. M. Karabacak, V.S. Perić, S.Z. Hassan, L.M. Fernández-Ramírez, L, „Novel Improved Adaptive Neuro-Fuzzy Control of Inverter and Supervisory Energy Management System of a Microgrid“ , Energies 2020, 13(18), 4721.

[7] S. K. Samboju, V. T. Tanjavooru, D. Zinsmeister, V. Peric “ Modeling of Combined Heat and Power Generation Unit for Dynamic Analysis of Integrated Thermal-Electric Grids” Workshop Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2021.

[8] R. Song, T. Hamacher, V. Perić, “Impact of Hydraulic Faults on the Electric System in an Integrated Multi-Energy Microgrids”, Workshop Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2021.

Stefan Hobmaier / TUM

Research

Doctoral Program at MSE

Coordination:
Dr. Christiane Hamacher
graduiertenzentrum@mse.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52706

www.mse.tum.de/promotion

MSE offers a wide range of opportunities for doctoral candidates in the field of energy. The focus is on interdisciplinary research topics, in line with the interdisciplinary and cross-faculty research conducted at MSE.

All doctoral candidates at TUM complete an accompanying qualification program during their doctorate that contains a number of mandatory as well as voluntary elements. The aim of the qualification program is to support the students by particularly promoting development of subject-specific skills. Therefore, workshops about Modelica, Python, Using R for Regression Analysis, Optimization under Uncertainty with Applications in Energy Markets and others have been organized. Moreover, the graduate center MSE organizes winter and summer schools, the last one dealing with the nexus between food and energy. Beyond this, all doctoral candidates are encouraged to present their research progress at the annual MSE-Kolloquium.

private

Participants and lecturers at the interdisciplinary winter school "Food and Energy" at the Science and Study Center Raitenhaslach in 2019

MSE has developed a program to support outstanding young research talents from Universities of Applied Sciences (UoAS) in the field of energy research. At the moment, the co-operation consists of six Bavarian universities:

- University of Applied Sciences Munich
- Technical University of Applied Sciences Rosenheim
- Deggendorf Institute of Technology
- Technische Hochschule Ingolstadt
- Weihenstephan-Triesdorf University of Applied Sciences
- Ostbayerische Technische Hochschule Regensburg

As part of the program, selected junior scientists from the UoAS become members both at the Graduate School and at the MSE Graduate Center, thus becoming co-operative students who participate in the accompanying qualification program at TUM.

Every project is supervised by one principal investigator (PI) from TUM and one PI from the UoAS. The progress of the projects is presented at the annual Ko-op Symposium in November. In addition, the doctoral candidates are offered the opportunity to become a member of a BayWiss-Verbundkolleg.

Winter Schools about Energy and Food

The Graduate Center of the Munich School of Engineering organized two winter schools on the Food-Energy-Nexus. The event in 2019 mainly focused on the topic food and was located at the Academy Center of TUM in Raitenhaslach. In the 2020 edition the main focus was on energy. The Hotel Alpenblick in Ohlstadt was the destination for the interesting presentations and fruitful discussions. The international and interdisciplinary environment with participants and lecturers from China, Finland, Israel, the Netherlands, Spain and Germany created a stimulating environment to explore the overarching challenges related to food and energy in times of urbanization, population rise and climate change. The PhD students and Post-Docs assessed sustainability aspects in food production and processing and discovered cutting-edge indoor cultivation related to energy demand and environmental impact.

Heinrich Kleeberger / TUM

Winter School 2020 in Ohstadt

Platform for International Exchange

The internationalization activities of MSE focused recently on international networking, workshops and facilitating scientific exchanges at its MSE colloquium and dedicated, topic-oriented winter schools.

Food-Energy-Water Nexus: Joint workshop with Israel

MSE hosted a three-day-workshop from November 2nd to November 4th, 2019 with researchers from TUM, the Ben Gurion University (BGU) in Israel and the Hochschule Weihenstephan Triesdorf in Freising (HSWT) at the Center for Energy and Information in Garching. The workshop was organized by Dr. Petra Liedl with financial support from the Bavarian Research Alliance. The aim of the workshop was a joint research proposal for the DFG Middle East program to foster collaboration. Beyond this, MSE is planning to intensify the co-operation through mutual guest lectures at both universities and co-supervised theses at TUM and BGU.

Research Workshop on Energy with Imperial College London

A scientific exchange on energy research has been initiated between Munich School of Engineering (TUM) and Energy Futures Lab (ICL). The collaborative virtual workshop series took place from October to December 2020 thanks to the support from the TUM Global Incentive Fund, as part of the strategic partnership between the two universities. It is the ambition to foster and support collaboration in the long term, as both are members of the Global Alliance of Technological Universities and can jointly apply for European grants. The consolidated results will facilitate and support near future collaborations between the academic partners. Each of the seven individual workshops were topic-oriented and accompanied by keynotes from both sides, subsequently followed by breakout sessions for further in-depth discussions on a principal-investigator level.

Cross-Cultural Presentations

As a side-activity MSE has established Cross-Cultural presentations in order to increase diversity and inter-cultural competencies. TUM-members with international backgrounds are encouraged to provide insights into their cultural and historical national heritage. These events are open to all MSE members and affiliates.

International Collaborations

Centered around CoSES a couple of international co-operations have been successfully established. Some of the successful examples are as Brazil, Russia and China. Internationalisation on project-level is also further increasing: Associated to the Geothermal-Alliance Bavaria, a joint project between NTU and TUM.Create in Singapore has been launched in 2020.

MSE Colloquium

Another main pillar to support diversity within TUM across faculties and research disciplines is the annual MSE Colloquium, a lively exchange platform for Bavarian researchers. This colloquium has expanded throughout the years. While the 2019 edition was still in a presence format, the 2020 edition needed to be shifted into the virtual space due to the pandemic. Despite the COVID-19 pandemic and the imposed challenges, the virtual events were still a huge success, as it is one of the few instruments and measures to link with new colleagues.

Students at the poster session of the MSE Colloquium

Geothermal Alliance Bavaria (GAB)

Prof. Dr. Thomas Hamacher
ens@ei.tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52740

www.mse.tum.de

Coordination:

Dr. Maximilian Keim
maximilian.keim@tum.de
Munich School of Engineering
Geothermie-Allianz Bayern

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 10641

www.gab.mse.tum.de

The successful development of deep geothermal energy in Bavaria is evident from the increasing number of projects realized to date. In order to further increase the economic viability of the technology, the enormous geothermal potential must be used as smart and as efficiently as possible. The aim should be to extract the resource safely and sustainably with a long term perspective in order to benefit in the long run.

The Geothermal Alliance Bavaria (GAB) is a joint research project, funded by the Bavarian State Ministry of Science and Art. Initiated in 2016, it enables a close co-operation of engineers and geoscientists and thus develops deep geothermal energy beyond the boundaries of its classical disciplines. The research work of the GAB not only enriches the scientific community but also provides specific solutions to current operational problems. The continuation and expansion of the GAB research network in its second phase until the end in 2024 has the objective to ensure that deep geothermal energy plays a major role in the future energy market. The integration of the Ludwig-Maximilians-University Munich (LMU) and the University of Applied Sciences Munich (HSM) into the GAB consortium from 2021 onwards, alongside the founding members in 2016, the Technical University Munich (TUM), the Friedrich-Alexander-University Erlangen-Nuremberg (FAU) and the University of Bayreuth (UBT), allows for additional expertise in Bavaria by addressing new scientific challenges. In total, 9 different TUM chairs and professorships contribute to GAB:

- Chair of Computational Modeling and Simulation
- Chair of Engineering Geology
- Chair of Hydrogeology
- Chair of Renewable and Sustainable Energy Systems
- Chair of Structural Mechanics
- Chair and Test Authority of Foundation Engineering, Soil Mechanics, Rock Mechanics and Tunnel construction
- Professorship of Data Analytics and Machine Learning
- Professorship of Geothermal Technologies

All research activities of the GAB are pro-actively linked and co-ordinated via the Munich School of Engineering (MSE). The task of project management is to ensure the continuous transfer of knowledge and the co-operation with operators, institutes and authorities and to build up an extensive database.

1st Phase 2016 – 2020

The first phase of the research project was divided into five work packages, the master's program and the project co-ordination. The most important results are summarized below.

Characterization of the hydrothermal reservoir

This work package aimed to reduce the exploration risk of geothermal projects in the Molasse Basin. For this purpose, the hydraulic, thermal and mechanical dynamics of the reservoir were investigated using the comprehensive data base in the GAB. It was found that the reservoir in the southwest of the Molasse Basin has much more of a heterogeneous matrix, which is associated with higher exploration risks. New detailed interpretations of the inflow zones around boreholes, their expression, and the hydrochemical nature of the reservoir provided important information for the planning and placement of geothermal doublets. A risk assessment of local stress redistributions in the Munich area by means of simulations was able to show that the injection of thermal water into critically pre-stressed faults can significantly increase the probability of micro seismic events. In the second project phase, the installed fiber optic cable (Fig. 1) in the geothermal project Schäftlarnstraße will serve as a monitoring tool for pressure and temperature, as well as the monitoring of micro seismic events. This will significantly contribute to the sustainable and efficient management of the reservoir.

Schölderle / TUM

Fig. 1.: Installation of the fibre optic cable in a geothermal borehole.

Operational safety in the thermal water circuit

In this work package, the formation kinetics of scaling has been experimentally investigated via hydrogeochemical models. First results for suitable countermeasures to reduce or even prevent the formation of scaling were carried out. An electrical condition monitoring of the submersible electrict centrifugal pump, which enables the detection of errors in the electrical system already at an early stage, increases the fault tolerance and partly the efficiency of the pump motor. An accurate model and an innovative control were developed. Both modeling and control scheme were successfully verified by simulations and measurements with a model-scale laboratory setup.

Efficient and flexible power plants

An ORC test rig with efficient and flexible heat extraction for combined heat and power has been developed and successfully operated in this work package. This laid the foundation for a comprehensive economic analysis of various other topics, such as working fluids, material compatibility and power plant concepts. The new environmentally friendly ORC working fluids were successfully tested at the test rig. Moreover, on the component level, a newly developed innovative condenser design enables significant cost savings. Potential analyses in terms of geothermal potential maps for heat and power production as a function of heat demand were quantified for southern Bavaria.

Monitoring

In this work package, measurement and operational data of existing geothermal plants were systematically investigated. Therefore, a set of key performance indices and simulations models have been developed and customized. Plant modeling and simulation calculations were fundamental elements for the development of analysis and diagnostic functions integrated into a user interface, showing the condition monitoring and the optimization potential. For example, a new methodology was developed for monitoring submersible centrifugal pumps regarding undesired scalings and for economically optimizing the maintenance of this critical component.

Petrotherm

In this work package, the heat anomaly in northern Bavaria was explored as a potential location for a future enhanced geothermal system (EGS) pilot project. For this purpose, among other things, the structural framework conditions, the interface inventory and the fault kinematics of the region were investigated, and databases of temperature data from existing boreholes and the petrophysical characteristics of rock types were built up and evaluated for the focus area in northern Bavaria. The core task was a successful 2D-seismic measurement campaign in the 'FAU Geotherm' scientific permit field. The evaluation and preliminary interpretation of the seismic data indicate promising structures for the exploitation of geothermal energy. However, for a detailed reservoir characterization and geothermal potential assessment, further geophysical data need be collected in the future.

Joint-Degree Master's Program

GAB / TUM

Fig. 2: Event of the GAB in 2019; students in exchange with geothermal plant operators.

The joint-degree master's program „GeoThermie/GeoEnergie" has a unique position in Germany's academic education and serves the following goals: (i) to provide a holistic spectrum of teaching content, from the exploration and development of geothermal resources using modern methods to their use and storage, (ii) to promote innovative,

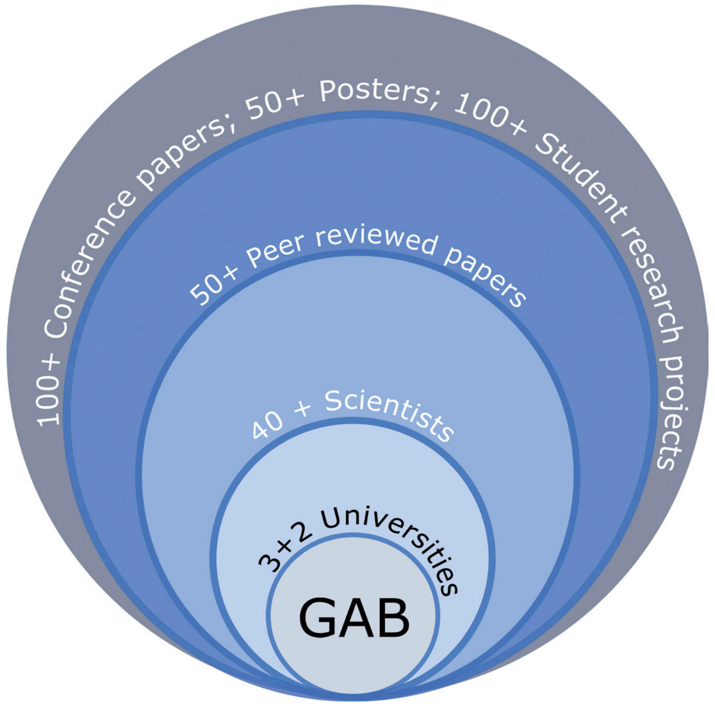


Fig. 3: Schematic representation of the scientific output of the GAB.

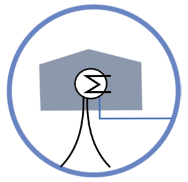
interdisciplinary thinking and action in the exploration and use of geo-energy resources, and (iii) to combine teaching and research expertise relevant to geo-energy resources from a total of eight faculties at FAU, TUM and LMU across disciplines and locations, as well as lecturers who contribute up-to-date knowledge from professional practice (Fig. 2). This practical relevance through case studies tailored to the subject of study and direct contact with geothermal operators is rated particularly positively by students in evaluations as part of the quality management.

The holistic research approach of the GAB has proven to be a success in answering important research questions in the first phase (Fig. 3). The GAB has successfully established itself, proven by the number of scientific publications and conference papers as well as media presence.

2nd Phase 2021-2024

The second phase of the GAB until 2024 investigates newly identified research topics and will serve as continuous contact for the national and international geothermal community as well as the public. To further increase the economic viability of the technology, the enormous geothermal potential must be exploited as sustainable and efficient as possible. The aim should be to extract the resource safely and in a long term manner, in order to benefit in the long run. Deep geothermal energy shows its strengths, especially for central heat supply in metropolitan areas. In order to make a greater contribution to the decarbonization of district heating and at the same time increase the utilization of geothermal plants, heat sources and heat sinks can be interconnected and linked over greater distances. Predicting the discoverability and thus the productivity of heat sources is not always possible in all parts of the southern Bavarian Molasse Basin, and in many places it is still subject to high uncertainties. In order to play an even greater role in Bavaria, the technology of deep geothermal energy should additionally be applied beyond the southern Bavarian Molasse Basin. In this context, explorative measures in combination with innovative concepts of deep geothermal energy should open up new ways to more clearly identify the potentials that have not been exploited so far. Furthermore, pathways have to be identified to guarantee a reasonable integration of the technology into the existing energy system. The overall research objectives for the second funding period can be summarized as follows:

- Intelligent and versatile use of geothermal heat
- Regional development of geothermal energy throughout Bavaria
- Increase in social acceptance through safe technology
- Long-term and sustainable management of the resource
- Training and information in the context of technology



Efficient – Heat transition through the intelligent use of deep geothermal energy

The work package 'Efficient' deals with the mechanical, electrical or thermodynamic plant components of geothermal energy utilization. The overall goal of the research is to improve the geothermal heat utilization and thereby to increase the economic efficiency. In addition to new approaches for electrical submersible pump motors, which promise higher efficiencies and thus lower power consumption, experimental investigations of new cycle processes are carried out on the existing test rigs for thermodynamic cycles. In this way, the technical feasibility of e.g. the triangular processes is investigated and new working fluids are tested. Innovative and more environmentally compatible organic working fluids should be tested and evaluated for their suitability, such as material compatibility or for use in high-temperature heat pumps. The use of geothermal energy is to be made more flexible by investigating and demonstrating the use of reversible heat pumps. In addition, concepts using CO_2 as heat carrier and working media are being pursued in order to consider new and interesting approaches. A dedicated concept for sorption refrigerators is researched, which can use decentralized geothermal district heating to generate cold for air conditioning.

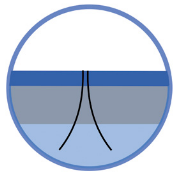
Regional – Systematic exploration of new potentials

Unexploited geothermal resources in northern Bavaria are being intensively investigated, in order to systematically explore new potentials. Furthermore, optimally suitable locations for a potential analysis of the district heating supply are to be selected for proven geothermal resources in southern Bavaria. In order to enable the use of deep geothermal energy in the crystalline region of Northern Bavaria, suitable sites are identified in the area of the geothermal heat anomaly in the Bamberg-Coburg region. The anomaly is investigated using a method-mix combining geophysical measurements, hydraulic characterization in the field and numerical modeling. The use of deep geothermal energy in Bavaria is mainly concentrated on the hydrothermal resources in the Molasse Basin in southern Bavaria. However, the potential for district heating in particular is far from being fully exploited. Therefore, two locations optimally suited for geothermal district heating supply are to be identified in the Molasse Basin for a detailed analysis of the above ground potential.

Social – Climate protection through a safe technology

Public acceptance for deep geothermal energy is addressed in this work package. Therefore, the safety and environmental protection aspects in geothermal projects will be assessed thoroughly. With regard to safety, induced seismicity particularly also plays a key role. Noticeable micro-seismic events recently occurred due to the geothermal heat extraction from the Molasse Basin. These harmless events have raised quite some public concern against geothermal exploration. Due to this, a risk analysis and probability assessment of the occurrence of eventual building damages caused by repetitive micro-seismic events is carried out by means of simulations. Another focus of this research project deals with the question of preventing such micro seismic events. Moreover, a comprehensive full life cycle analyses in deep geothermal energy is part of this work package.

Long-term – Sustainable thermal water production



This work package examines issues concerning the exploration, drilling, and production risks in the Bavarian Molasse Basin as well as sustainable reservoir management. A holistic approach is therefore proposed, incorporating various key parameters (temperature, hydraulics, tensions/mechanics, and hydrochemistry) on a larger scale. The Bavarian Molasse Basin is of primary focus to investigate as an overall geothermal system. Possible impacts of the different structural units of the Bavarian Molasse Basin on the exploration, development and productivity of the Malm reservoir are key areas of interest. The petrophysical and geomechanical characterization of the reservoir, as well as the interacting structural units of the Bavarian Molasse Basin are advanced using the drilling & production data, drill cores, analog samples and laboratory analyses. The knowledge accumulated during the course of the research will further be implemented in site-specific investigations for the development of forecasting and monitoring tools to ensure sustainable reservoir management and reduce the drilling risks.

Project management

An example is the GAB's knowledge transfer (Fig. 4), which is a regular exchange platform between academia and industry. So far, these events experienced great interest and anticipation of the geothermal community. In addition, the GAB hosts workshops and conference sessions at major conferences like the DGK or the Praxisforum Geothermie. Bayern.

The GAB project management is also involved in international projects. For example, it is currently developing a guideline for the collection of minimum data for geothermal exploration wells on behalf of the Swiss Geothermal Association. Since 2020, it has been involved in a geothermal exploration project with the Nanyang Technological University in Singapore. The GAB co-ordination team also takes care of the public relations of the project, which involves for instance the monthly publication of newsletters and the operation of social networks and communication channels. Furthermore, the GAB is available as a point of contact for the general public regarding deep geothermal energy. Moreover, the project office supports also municipalities with technical questions.

Mark Fernandes

Fig. 4: Presentation of the results of the Master Plan Geothermal Energy Bavaria at the Praxisforum Geothermie.Bayern

Publications:

Bohnsack, D., Potten, M., Pfrang, D., Wolpert, P. & Zosseder, K. (2020): Porosity-permeability relationship derived from Upper Jurasssic carbonate rock cores to assess the regional hydraulic matrix properties of the Malm reservoir in the South German Molasse Basin. Geothermal Energy 8, 12 (2020), https://doi.org/10.1186/s40517-020-00166-9.

Dawo, F.; Wieland, C.; Spliethoff, H. (2019): Kalina power plant part load modeling: Comparison of different approaches to model part load behavior and validation on real operating data. Energy 174 (2019) 625-637. https://doi.org/10.1016/j.energy.2019.02.173.

Drews, M.; Seithel, R.; Savvatis, A.; Kohl, T.; Stollhofen, H. (2019): A normal-faulting stress regime in the Bavarian Foreland Molasse Basin? New evidence from detailed analysis of leak-o� and formation integrity tests in the greater Munich area, SE-Germany. Tectonophysics 755 (2019) 1–9. doi.org/10.1016/j.tecto.2019.02.011

Eyerer, S.; Schifflechner, C.; Hofbauer, S.; Bauer, W.; Wieland, C.; Spliethoff, H. (2020): Combined heat and power from hydrothermal geothermal resources in Germany: An assessment of the potential, Renewable & Sustainable Energy Reviews, vol 120, https://doi.org/10.1016/j.rser.2019.109661.

Heine, F., Einsiedl, F. (2020): Groundwater dating with dissolved organic radiocarbon: a promising approach in carbonate aquifers. Applied Geochemistry, vol. 125, doi.org/10.1016/j.apgeochem.2020.104827.

Köhl, B., Elsner, M. & Baumann, T. (2020): Hydrochemical and operational parameters driving carbonate scale kinetics at geothermal facilities in the Bavarian Molasse Basin. Geothermal Energy, Geothermal Energy 8, 26, https://doi.org/10.1186/s40517-020-00180-x.

Potten, M., Sellmeier, B., Mraz, E., & Thuro, K. (2019): Geomechanical Investigation of High Priority Geothermal Strata in the Molasse Basin, Bavaria, Germany. In IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018-Volume 2 (pp. 21-26). Springer, Cham.

Wieland, C., Spliethoff, H., & Baumann, T. (2020): CO_2-neutral co-produced gas utilization for deep geothermal applications. Geothermics, 88, 101895, https://doi.org/10.1016/j.geothermics.2020.101895.

SekToRkOpplung und Micro-grids - the STROM Research Alliance

Speaker:

Prof. Dr. Thomas Hamacher
Thomas.hamacher@tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52700

Coordinator:

Dr. Vedran Peric
vedran.peric@tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52720

Starting in 2021, MSE will coordinate the Bavarian Research Alliance STROM with a total of nine sub-projects, comprising four different academic partners (TUM, TH Rosenheim, TH Ingolstadt, Hochschule München) and a total of 26 industrial partners. Centered around the CoSES, STROM is aiming to create a cluster of excellence that investigates the potentials of sector coupling and systems integration in the Bavarian context with the focus on microgrids in the future energy system. The Research Alliance reviews the current state of the different energy sectors and analyzes their roles in the future carbon-free energy system. It performs research to develop promising technologies that will enable this transition.

The transition to more climate friendly energy systems imposes significant changes in expansion planning and operation. These changes are characterized by intensive exploitation of renewable energy sources and more efficient operation of the system using intelligent control as well as information and communication technology. Most renewable energy sources, such as wind and solar, generate electricity as the de facto new primary source of energy. Considering that electricity can be easily converted to different types of energy and the trend of extensive electrification of heating, cooling and transportation sector, electricity is widely recognized to play a crucial role as the backbone of the future sector-coupled energy system.

Another important aspect of the vision of the future carbon-free and efficient energy system is the concept of microgrids. Microgrids are independent energy entities within certain regional boundaries that improve the security of energy supply through decentralized operation and control.

It is envisioned that the Bavarian Research Alliance STROM, together with the CoSES laboratory, will become the leading platform for open exchange among relevant stakeholders where the resulting energy transition concepts and technologies can be validated in laboratory scale using the know-how of the partners involved in the project.

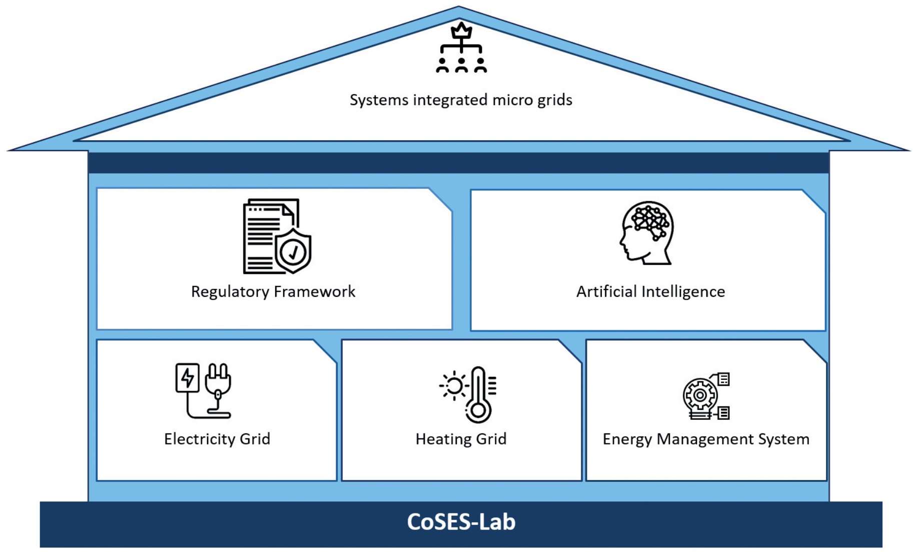


Fig.1: Schematic structure and topics of the STROM research alliance, based on CoSES research infrastructure as a shared facility

The project activities will focus on the following main research directions:

- Assessment of the overall Bavarian en ergy potentials and regulatory framework,
- Application of artificial intelligence in the future energy system,
- Design and operation of electric power system,
- Design and operation of district heating system,
- Design and operation of building stock.

These five aspects will be addressed in a holistic manner to find the optimal strategy of the energy system development. In addition, the project will contribute to the technology development that is seen as a critical for wider acceptance of sector-coupled micro-grid concept, such as innovative thermal storages, heat pumps and building management systems.

Multi-Energy Management and Aggregation Platform (MEMAP)

Contact:
Thomas Lickléderer, M.Sc.
thomas.licklederer@tum.de
Munich School of Engineering

Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52757

www.mse.tum.de
www.memap-projekt.de

The research project "Multi-Energy Management and Aggregation Platform" (MEMAP) develops a software platform that optimizes and coordinates the energy flows in smart neighborhoods during operation. The objective is to enable and use sector coupling between the heating and electricity sector and at the same time exploit synergies between the different demand profiles as well as generation and storage capacities of the participating units in the neighborhood. This leads to a higher system efficiency and savings in energy, costs and CO_2 emissions for the neighborhood as a whole. The platform connects different local Energy Management Systems (EMS) in the neighborhood (see Fig.1). For the communication the industrial communication protocol OPC UA is used. The platform aggregates data from these EMS and uses the information to optimize the generation schedule. The optimized schedule with a time resolution of 15 minutes is reverted to the local EMS as setpoints for the power flows. The EMSs are responsible for implementing these setpoints autonomously in the individual devices.

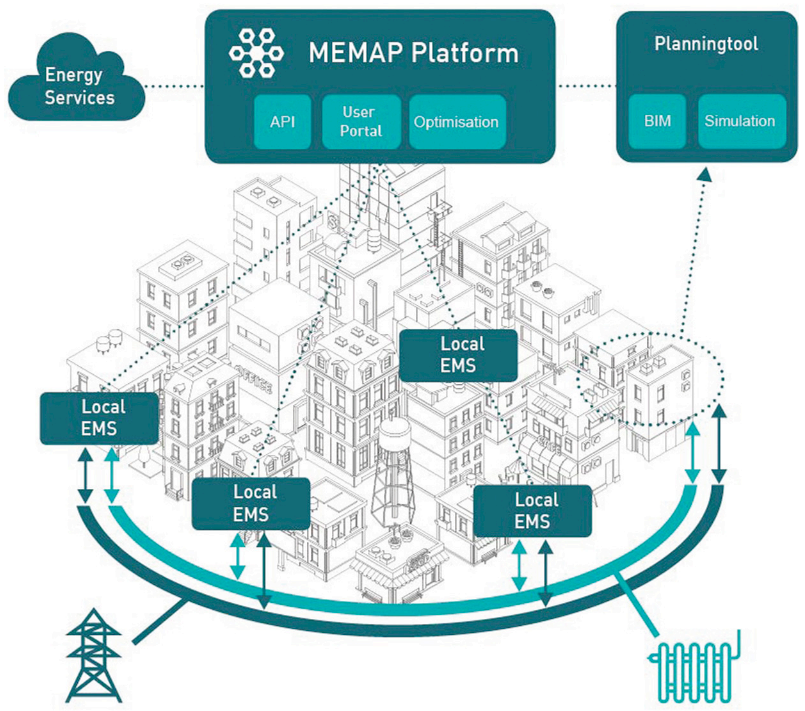


Fig. 1: Concept of the MEMAP research project

As academic project partner, the Munich School of Engineering (MSE) is mainly involved in the development of algorithms and models that enhance the smart management functionality of the platform. These algorithms and models are part of the kernel that uses predefined device classes comprising all relevant types of devices in neighborhoods: (i) controllable producers, (ii) volatile producers, (iii) couplers (of heat and electricity sector), (iv) storages and (v) demands. Exemplary devices belonging to those classes are: (i) gas boilers, (i) photovoltaic systems, (iii) heat pumps, (iv) battery storage systems, (v) heating demands of building. The model predictive controller (MPC) in the kernel of the platform is able to consider time variable prices and automatically features smart buying or selling of energy from the public grid as well as anticipatory charging and discharging of storages. Therefore, it uses internal models of the neighborhood including its devices and forecasts for the future demands, generation capacities and prices that are provided by external sources.

Apart from the developed platform for the online operation of neighborhoods, a planning tool was developed using the same kernel. A user-friendly and human-centered graphical user interface (GUI) has been set up together with the project partner fortiss. The planning tool allows to simulate user-defined constellations using different settings, without actual devices being connected. This can support e.g. the planning and scheduling of modifications like extensions of the cluster or the replacement of devices. The planning tool provides the user with a nice perfect overview on possible cost and CO_2 emission savings. The planning tool including the kernel is accessible open source under **https://github.com/SES-fortiss/SmartGridCoSimulation**.

In the years 2019 and 2020, the first kernel versions from previous years were evolved: in order to reflect heating or cooling networks on the thermal side, the kernel was extended to consider networks with incomplete connection graphs and percentage heat losses. Further, the behavior of real devices being restricted to run either between a non-zero minimum and a maximum power or being turned off should be reflected. This was done by adding suitable modelling constraints to the optimization problem in the kernel of the platform, converting the problem into a mixed-integer linear problem (MILP). In addition, the storage model in the kernel was refined to also reflect the effect of standby-losses over time. This is relevant in particular for thermal storages that discharge continuously to the environment due to the temperature difference and imperfect insulation even in standby mode without being actively used. Also some studies were done on the integration of a model for thermal storages that reflects the temperature layering in thermal storage tanks.

Besides the software-side, the MSE is involved in the testing and validation of the MEMAP platform. As the originally intended test area in Riemerling turned out to be unavailable for the implementation part of MEMAP, the Center for Combined Smart Energy Systems (CoSES) at MSE was chosen to test the platform operation in interaction with real devices. The acquisition of data and user-feedback is still done in Riemerling.

In the final stage the CoSES laboratory will emulate a neighborhood with the technical equipment of 5 buildings including a thermal network and a microgrid connecting these emulated buildings. The MEMAP platform is tested as one of the first projects in the laboratory environment. Therefore, the MEMAP-team supported the construction works and the commissioning of the laboratory environment. Objectives of the test runs of MEMAP in CoSES are a proof-of-concept and can be considered as a validation of the developed platform and software architecture, including communication and interface concept in interaction with real devices. Therefore, a minimum scenario with two buildings was chosen. The MEMAP-team worked close together with the colleagues from CoSES to set up the scenario with the real hardware and the necessary software chain in the laboratory.

The scenario includes two 800-liter heat storage tanks and two heat sinks (load emulators), a condensing boiler with 21 kW_{th} output and a CHP unit with 2 kW_{el} and 5 kW_{th} output. Additionally, the buildings are connected via a thermal and an electrical grid.
The MEMAP platform is integrated into the CoSES environment as illustrated in Fig. 2. MEMAP is installed on a host computer, the simulation of the individual EMS is carried out via customized models. For the communication between the platform and the real devices, a standardized information model including naming conventions was defined. The data and information model is compatible with the OPC UA communication standard. It increases portability and allows to make existing EMSs “MEMAP-ready”. In order to co-ordinate and synchronize the MPC-procedure in the kernel of the platform and the communication process from/to various data sources and sinks, a sequence concept for the operation with real devices was implemented. It guarantees that all aggregated data (including forecasts) refer to the same discrete time steps, all data is available at the same time at the platform for optimization and also simultaneously reverted to all the connected EMSs.
The laboratory tests run in real time over periods of 8 to 36 hours. The final tests will start in summer 2021.

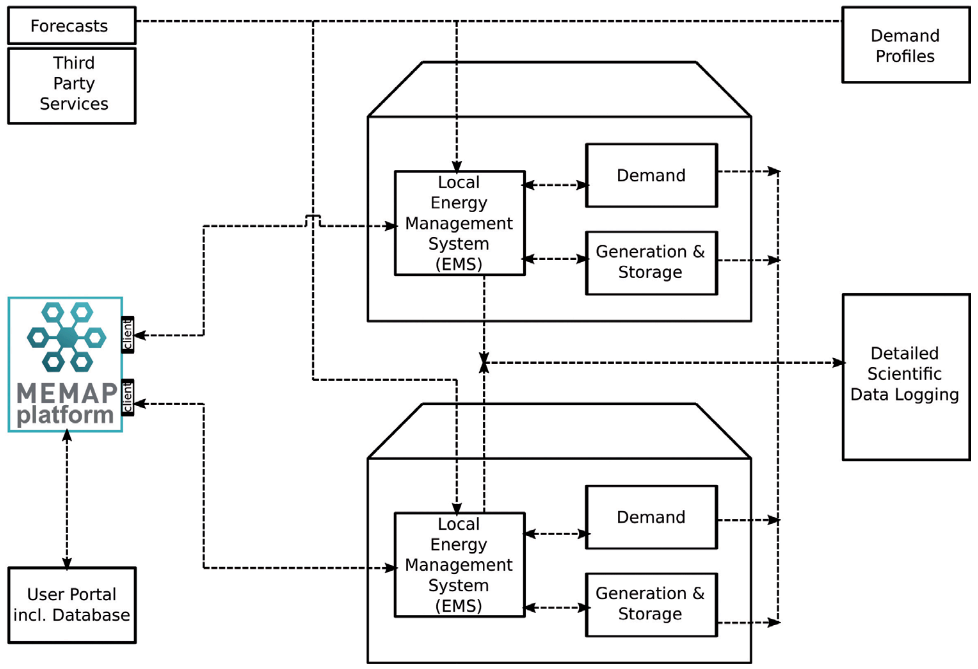


Fig. 2: Integration of the MEMAP platform in the CoSES laboratory

MEMAP does cross-sectoral energy management of neighborhood clusters at the level of energy and power flows. Thinking especially beyond the thermal side, an important research question is how the resulting power setpoints can be implemented on the technical level, e.g. in terms of volume flows, temperatures and pressure differences. This question is related to thermal networks with decentralized prosumers as a future replacement of centralized conventional district heating systems. Prosumers are entities that can act as consumers or producers to the overarching energy system and switch between these modes over time. A thermohydraulic model of Smart Thermal Grids with

bidirectional power flow between prosumers was developed and published. Assuming a suitable reference network architecture, the derived system of equations interlinks the control variables of such networks with their thermohydraulic steady-state. Explicitly considered are the heat transfer to the secondary side, flexible prosumer modes and the behavior of decentralized control pumps and valves depending on their control inputs. To investigate the network behavior a python-based simulation framework is provided open source under **https://github.com/thomaslicklederer/ProHeatNet_Sim**. In a next step, the model shall be modified to a control model for the operation of prosumer-dominated thermal networks.

One assumption of the project concept is that all participants in a neighborhood cluster using MEMAP act collaboratively as a kind of energy community that wants to optimize the overall welfare. This assumption allows to focus on the technical implementation and avoids market considerations. However, the question arises, how the costs for operating the decentral devices are shared amongst the participants in such a way that everybody has an incentive to keep participating in the energy community.
Within a student thesis different concepts from co-operative game theory like the core, nucleolus and shapley value were investigated for this purpose. One conclusion was that cost allocations from co-operative game theory are not really practical for this application as their calculation requires the optimization process to be performed for N participants up to 2N-times. So only for small numbers of players they are computable in manageable time.

The consortium of the MEMAP project consists of 6 partners: fortiss, Sauter-Cumulus, MSE, Holsten Systems GmbH, IBDM GmbH and Zentrum Digitalisierung Bayern (now Bayern Innovativ). Together, an interactive user portal for the MEMAP platform was developed. The user portal can be coupled with the MEMAP platform in order to start and control the operation of the platform and visualize results. In the field test area in Riemerling thermal and electrical consumption data was measured. This data will be analyzed and adopted for the validation tests of the platform in the CoSES laboratory. Further, the gathered data and the MEMAP planning tool were combined to conduct studies on economic aspects and possible energy savings for the reactivation or reconstruction of the thermal network in Riemerling. A building information model (BIM) of the site in Riemerling was created using a drone-based method.

The automation of the interaction between BIM-models and the MEMAP platform is a work in progress. This can simplify the parameterization of MEMAP and lead to an illustrative visualization of the results of the energy management in the neighborhood. Interviews with potential customers and users of the MEMAP platform in Riemerling on the acceptance of such a concept were conducted and analyzed. The results show that idealism is the main driver for the interest in concepts like MEMAP. A sense of community as well as motivated and committed individuals are a necessary criterion for the success. However, financial benefits and no extra effort are the most important aspects.

The project concept and its results are presented on the project website (www.memap-projekt.de) administrated by the Zentrum Digitalisierung Bayern (now Bayern Innovativ). Workshops and Webinars with business networks (e.g. https://www.smartq-netzwerk.de/) and fairs (i.e. TechDays Munich and the Hannover Messe) as well as the participation in conferences were part of the dissemination strategy within the project. In autumn 2019 the Projektleitertreffen of the research network "EnergieWendeBauen" was hosted by the MEMAP team at MSE (see Fig. 3). Scientific Publications and articles that were published in professional magazines can be found below in the publication list.

Fig. 3: Project Meeting EnergieWendeBauen 2019 at MSE

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Aggregationsplattform zur gebäudeübergreifenden Optimierung der Energieeffizienz, Teilvorhaben Modellierung, Optimierung und Simulation Energiesysteme" (MEMAP, FKZ 03ET1413B) is funded by the German Federal Ministry for Economic Affairs and Energy.

Duration:
01.06.2017-30.09.2021

Publications:

Heidemann, L., Bytschkow, D., Capone, A., Licklederer, T., & Kramer, M. (2019). Sector Coupling with Optimization: A comparison between single buildings and combined quarters. Abstracts from the 8th DACH+ Conference on Energy Informatics, 2(S2), 29–33. https://doi.org/10.1186/s42162-019-0098-7

Licklederer, T., Capone, A., & Kramer, M. (2019). Poster: Multi-Energy Management and Aggregation-Platform. 9th Energy Colloquium of the Munich School of Engineering - Shaping a Sustainable Energy Future.

Bytschkow, D., Capone, A., Mayer, J., Kramer, M., & Licklederer, T. (2019). An OPC UA-based Energy Management Platform for Multi-Energy Prosumers in Districts. 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 1–5. https://doi.org/10.1109/ISGTEurope.2019.8905725

MEMAP Research Group. (2020). Nachhaltige Quartiere realisieren. Entwicklung einer Softwareumgebung für die Gebäude- und Sektorkopplung. Heizungsjournal, 1-2 2020

MEMAP Research Group (2020). Werkzeuge für die Realisierung von nachhaltigen Quartieren – Regelung und Steuerung der Gebäude- und Sektorenkopplung. Netzpraxis, März 2020

MEMAP Research Group (2020). Werkzeuge für die Realisierung von nachhaltigen Quartieren – Softwareumgebung zur Regelung und Steuerung der Gebäude- und Sektorenkopplung. BWKenergie, 4-5 2020

Licklederer, T., Hamacher, T., Kramer, M., & Perić, V. S. (2021). Thermohydraulic model of Smart Thermal Grids with bidirectional power flow between prosumers. Energy, 230, 120825. https://doi.org/10.1016/j.energy.2021.120825

Optimized Sector Coupling in Districts through Intelligent Thermal Prosumer Networks – OSkit

Dr. Vedran Peric
vedran.peric@tum.de
Munich School of Engineering
Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 52720

Dr.-Ing. Peter Tzscheutschler
ptzscheu@tum.de
Munich School of Engineering
Lichtenbergstr. 4a
85748 Garching
Tel.: +49 89 289 28304

www.mse.tum.de/MSE

The transition from a fossil-fuel-based to a renewable-dominated energy system must include the three essential sectors, which are electricity, heat and transport. The coupling of the electricity and heating sectors is an effective and cost-efficient tool to compensate for fluctuations of volatile, renewable electricity generators and to reduce the load on the distribution grid.

Stefan Hobmaier / TUM

Fig. 10: Conventional decentralized (left) and centralized (right) approaches to heat supply are combined to form a prosumer-based heat network (center)E

Current approaches in the coupling of electricity and heat sectors predominantly follow a strict decentralized or centralized approach for heat supply. In the traditional decentralized approach, the individual consumers, such as residential buildings locally have own generation units, like gas boilers to satisfy their heat demands. On the other side conventional district heating systems are a centralized approach where one or a few central heat generation units (mostly CHP or geothermal plants) supply heat unidirectionally to the consumers. In the OSkit project a combination of both approaches will be investigated: Former consumers become prosumers (=producer + consumer) that locally have generation units but at the same time are connected within a smart heating network. The network allows them to bidirectionally exchange energy. That shall reduce the necessary capacity of big and slow central generation units. The whole system becomes much more flexible. Depending on the boundary conditions, like available renewable generation always the most efficient and sustainable devices can be used to supply the heat demand of a neighborhood. Decentral sources, like waste heat from production sites can be integrated easier. With respect to sector coupling this type of heat networks dynamically interacts with the electricity system by the operation of heat pumps and CHP units, where electricity needs to be withdrawn from or can be provided to the public grid. It is expected that thereby the heat sector can benefit from fluctuations in the electricity sector and at the same time with its intrinsic thermal inertia and storage capacities provide services such as peak shaving to the electrical grid.

The project will investigate technical approaches to implement district heating networks that follow the concept explained above. Additionally, suitable operation and control strategies, as well as market approaches for the local trade of thermal energy between the prosumers in a network will be elaborated. The functionality of this innovative concept for district heating will be analyzed with respect to the interaction with and the impact on electrical distribution grids.

In a first step, the investigations will be based on simulation studies with models that have to be developed or adapted. One crucial component for the technical implementation of this network concept is a bidirectional heat transfer station that interconnects the individual prosumers with the network and enables the energy transfer. For this and other relevant components concepts will be developed and compared. Based on that hardware prototypes will be designed and built. In the CoSES laboratory environment the hardware prototypes will be combined with the simulation models (Hardware-in-the-loop and Software-in-the-loop) and the developed operation and market strategies to validate the innovative thermal and electrical microgrid.

Finally, a field test validation will be prepared as a potential follow-up of the project. Suitable field test areas will be elaborated and techno-economic implementation options will be investigated.

TUM.solar

TUM's Keylab in the Bavarian SolTech network

Head:

Prof. Dr. Peter Müller-Buschbaum
muellerb@ph.tum.de
Chair of the Institute of Functional Materials
Department of Physics

James-Franck-Str. 1
85748 Garching
Tel.: +49 89 289 12452

www.tum-solar.mse.tum.de

New concepts for the controlled structuring of materials interfaces as well as the use of new materials for energy transformation and energy storage offer an enormous potential for pushing the utilization of renewable energies into new areas in the future. The use of nanomaterials, organic-organic, or organic-inorganic hybrid systems enables completely new concepts and visions of energy transformation and energy storage. In this respect, the key-lab TUM.solar is focusing on research in light-induced energy transformation and energy storage based on nanomaterials and hybrid systems. There is a wide range of possible solutions, from catalytic processes to low-cost photovoltaics. The respective fundamental challenges refer to aspects of materials preparation and charge transfer at interfaces. For this purpose, TUM.solar combines complementary investigations from theoretical and experimental research groups in physics and chemistry. TUM.solar is one out of five key-labs of the "Solar technologies go Hybrid Research Network" (SolTech), which is an interdisciplinary project initiated by the Free State of Bavaria to explore innovative concepts for converting solar energy into electricity and non-fossil fuels.

TUM.solar is headed by Professor Müller-Buschbaum. It covers the whole "value chain" from energy transformation up to energy storage and hereby researches on aspects of basic physical-chemical processes up to application-related questions such as the construction of devices. Shape and mobility of future generations of solar cells could reach completely new dimensions by the use of new fluid-based production processes. These offer new possibilities of use in mobile entertainment electronics as well as in the power production of mega cities. Furthermore, new materials allow alternative production processes leading to considerably reduced production costs and thus promising future low-cost power supply. A completely different attempt to store energy, far from nowadays' energy storage technologies, is offered by photocatalysis. Here, the concepts are based on new catalysis materials and guided structuring of electrolyte interfaces, which help to increase the conversion efficiency. Examples like photo-chemical reduction of carbon dioxide and water splitting are aspects, which can drive to the so-called "green technologies". In 2019 and 2020 the PIs working at TUM.solar were Prof. David Egger (Physics), Prof. Thomas Fässler (Chemistry), Prof. Katharina Krischer (Physics), Prof. Peter Müller-Buschbaum (Physics), PD Harald Oberhofer (Chemistry), Prof. Ian Sharp (Physics), and Prof. Martin Stutzmann (Physics).

From the very active research in TUM.solar, selected projects are introduced in detail in the following. These examples give an idea about the broad range of research activities at TUM.solar, covering topics about macroporous Ge and Si/Ge as well as porous Ge/C materials, synthesis and optoelectronic properties of transition metal nitride semiconductor photoabsorbers, GaN nanogrids as electrodes for efficient electro-photocatalysis, long-range response in halide perovskites, degradation mechanisms in organic solar cells probed with operando studies and charge transport in energy materials.

Macroporous Ge and Si/Ge as well as porous Ge/C materials

Macroporous materials offer a solid basis for the development of hybrid materials. Whereas commonly metal-oxide-based materials find applications in various fields, semiconductors with microporosity are scarcely available. The Fässler group described a synthetic protocol that allowed for the formation of germanium and silicon/germanium films that possessed a highly ordered macroporous structure (Fig. 1c). So-called inverse Opal structures that consisted of amorphous or crystalline (□-Ge) films were synthesized from soluble Ge9-clusters (Fig. 1b) by the Fässler group. This process was now transferred to mixed silicon/germanium film with tunable Si/Ge composition. The macroporosity was obtained by utilizing a polymer template (e.g. PMMA, Fig. 1a), which was removed after the deposition of the silicon/germanium solution. Decoration of mixed Si/Ge clusters with silyl groups (Fig. 1e) enabled the solubility of the cluster in a broad range of organic solvents and allowed for an expansion of the synthesis strategy. The well soluble functionalized Ge9-clusters were exploited to synthesize porous Ge/C-nanocomposites films (Fig. 1f). In this process, the incorporation of an additional polymer was no longer necessary since the cluster was soluble in the monomer (e.g. divinylbenzene, Fig. 1d). At the same time, the monomer functioned as the carbon source for the Ge/C films. Besides semiconducting properties, we investigated the potential of these materials as electrochemical anode. [1,2]

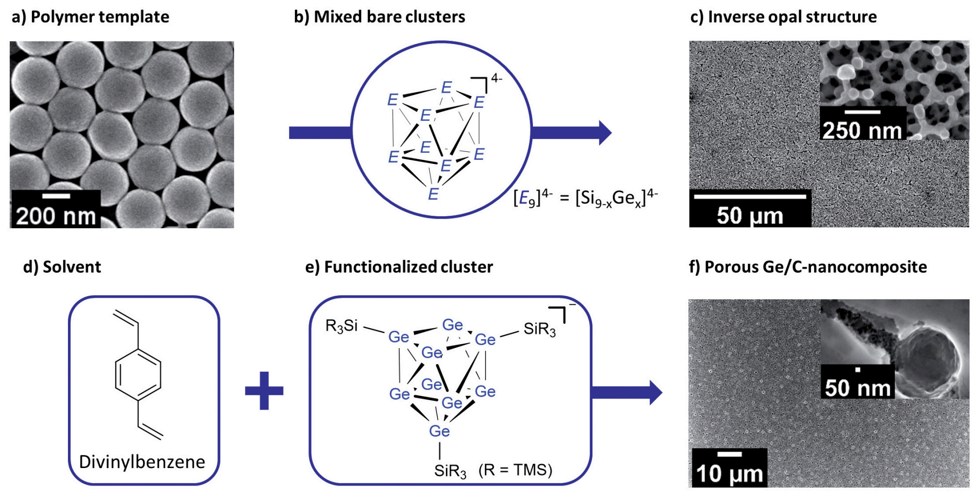


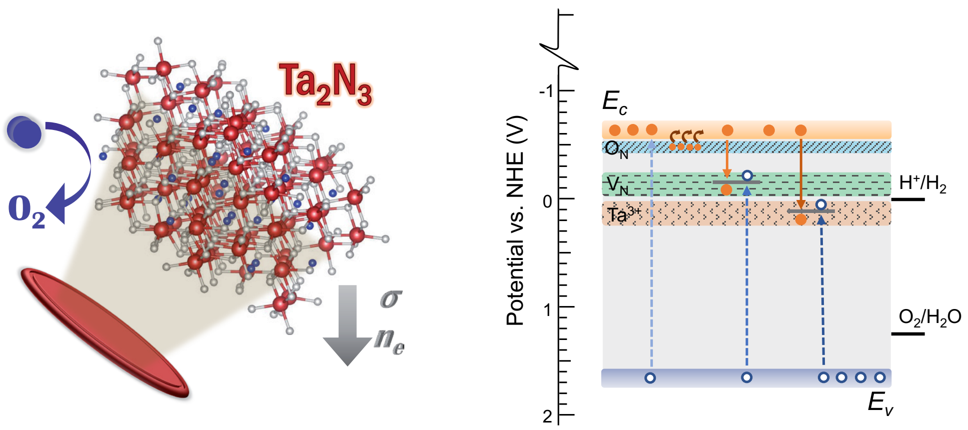
Fig. 1. Synthesis of inverse opal structures as well as porous Ge/C-nanocomposites based on tailored clusters.

[1] N. Hohn, A. E. Hetzenecker, M. A. Giebel, S. Geier, L. Bießmann, V. Körstgens, N. Saxena, J. Schlipf, W. Ohm, P. S. Deimel, F. Allegretti, J. V. Barth, S. V. Roth, T. F. Fässler, P. Müller-Buschbaum, Amphiphilic diblock copolymer-mediated structure control in nanoporous germanium-based thin films. Nanoscale 2019, 11, 2048.

[2] S. Geier, R. Jung, K. Peters, H. A. Gasteiger, D. Fattakhova-Rohlfing, T. F. Fässler, Wet-chemical Route for Macroporous Inverse Opal Ge Anodes for Lithium Ion Batteries with High Capacity Retention. Sustainable Energy Fuels 2018, 2, 85–90.

Synthesis and optoelectronic properties of transition metal nitride semiconductor photoabsorbers

The Sharp group worked on the development of advanced transition metal nitride (TMN) thin films for application in the sustainable conversion of sunlight to chemical fuels in a process known as artificial photosynthesis. These TMN semiconductors hold significant promise as photoelectrodes and provide a pathway to overcome several limitations associated with metal oxide materials, which historically have been much more in the research focus. For example, moving from transition metal oxides to analogous nitrides favorably affects the underlying electronic structure of the material. This enables more efficient visible light absorption without adversely impacting the driving force for light-driven oxidation reactions at the solid/liquid interface. In addition, the lower electronegativity of nitrogen compared to oxygen leads to mixed ionic-covalent bonds that can improve charge transport properties while retaining a high electronic tolerance to structural defects. Despite these advantages of TMN semiconductors, it is often difficult to synthesize these materials due to the high thermodynamic stability of molecular N2 and competitive reactions of transition metals with oxygen. These physical considerations demand the use of advanced non-equilibrium synthesis approaches.



(a) (b)

Fig. 2. (a) Illustration of the structure of Ta2N3, a metastable compound in which oxygen plays a dual role in enabling synthesis and controlling electrical conductivity over a broad range, enabling either semiconducting or metallic electrical transport. [3] (b) Energy level diagram for rhombohedral Ta3N5, a 2.1 eV bandgap semiconductor that is promising for solar water splitting. The energies of the conduction band (Ec) and valence band (Ev) are well poised for driving overall water splitting, but chemically reduced tantalum centers (Ta3+) lead to trapping and recombination, which significantly reduce performance. In contrast, substitutional oxygen (ON) and nitrogen vacancies (VN) are energetically shallower, with ON playing a key role in tuning electrical conductivity. [4]

In recent work, the Sharp group developed processes for reactive magnetron sputtering of a model transition metal nitride system, tantalum nitride, and explored the roles of defects and impurities on defining their structural and optoelectronic properties, as well as solar energy conversion efficiencies. Using this approach, it was found that small concentrations of oxygen are actually beneficial for stabilizing higher tantalum oxidation states, thereby allowing the formation of nitrogen-rich phases and semiconducting polymorphs.

Thus, by incorporating O2 into the sputtering environment, the metastable and rarely reported Ta2N3 phase can be directly prepared by reactive magnetron sputter deposition (Fig. 2a). On the other hand, the extent of oxygen incorporation can be controlled and used to tailor the optoelectronic properties of the nitride materials. In particular, oxygen impurity incorporation allowed the electrical conductivity of films to be varied over seven orders of magnitude. In related work, ammonia annealing was applied for the fabrication of a more nitrogen-rich phase, Ta3N5, which possesses a 2.1 eV bandgap and promising characteristics as a photoanode material. Using a suite of characterization methods applied to films with precisely controlled compositions, it was found that the major performance-limiting defect in the material consists of chemically reduced Ta centers, which trap charge carriers at unfavorable energetic levels. By contrast, oxygen impurities served as shallow donors to beneficially control the concentration of free charge carriers, which was essential for tailoring energetics and driving forces for charge separation (Fig. 2b). Overall, this work revealed a dual role of oxygen impurities in TMNs, for both facilitating the formation of metastable nitrides and tuning their electronic characteristics. Ongoing research is devoted to the development of entirely new semiconducting nitride compounds that have promising properties for use in artificial photosystems.

[3] C.-M. Jiang, L.I. Wagner, M.K. Horton, J. Eichhorn, T. Rieth, V.F. Kunzelmann, M. Kraut, Y. Li, K.A. Persson, I.D. Sharp, Metastable Ta2N3 with Highly Tunable Electrical Conductivity via Oxygen Incorporation, Materials Horizons, in press (2021) **https://doi.org/10.1039/D1MH00017A**

[4] J. Fu, F. Wang, Y. Xiao, Y. Yao, C. Feng, L. Chang, C.-M. Jiang, V.F. Kunzelmann, Z.M. Wang, A.O. Govorov, I.D. Sharp, Y. Li, Identifying Performance-Limiting Deep Traps in Ta3N5 for Solar Water Splitting, ACS Catalysis 10, 10316 (2020)

GaN nanogrids as electrodes for efficient electro-photocatalysis

Efficient photocatalysis and electro-photocatalysis require electrodes that must exhibit many different properties for an optimized performance. Photogenerated electrons and/or holes have to be delivered to the environment at the right energy levels to match the redox-levels of the targeted electrochemical reaction, they have to be able to conduct photoelectronic current at their surfaces with the right current density, they have to be photo-responsive in the relevant optical spectral range, and they have to be long-term stable under the required operational conditions. Among all semiconductors, Gallium Nitride (GaN) has received a lot of attention in this respect in recent years due to its favorable electronic and chemical properties. To enhance the current exchange with the environment and to engineer photonic properties of the GaN electrodes, periodic GaN nanostructures with feature sizes in the range of 100 nm have many advantages compared to flat GaN surfaces. Therefore, arrays of one-dimensional GaN nanowires have been extensively studied for photoelectrode applications in the recent past.

The Stutzmann group took this to the next dimension by developing periodic arrays of two-dimensional GaN nanowalls and nanogrids. Some examples are shown in Fig. 3. These nanogrids can have a surface area up to ten times higher than a flat surface, but still provide the advantageous properties of GaN overall. Due to the tuneable periodicity, the optical properties of such nanogrids can also be adapted to the spectrum of incoming radiation in a very flexible way [5].

[5] Winnerl, Julia; Kraut, Max; Artmeier, Sabrina; Stutzmann, Martin: Selectively grown GaN nanowalls and nanogrids for photocatalysis: growth and optical properties. Nanoscale 11, 4578 (2019)

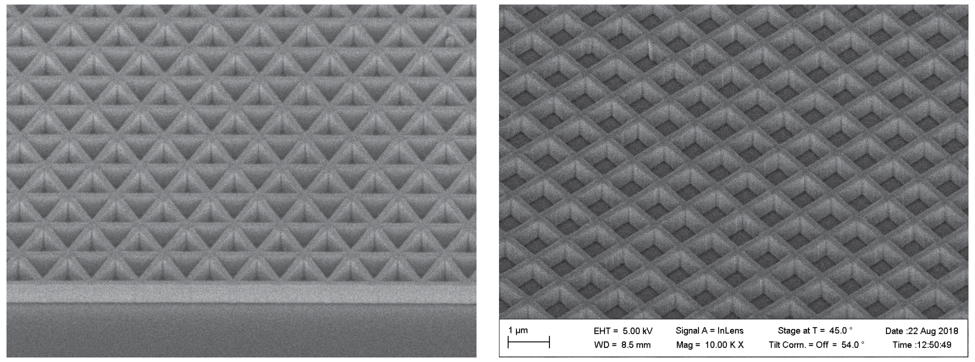


Fig. 3. Triangular and quadratic grids of GaN nanowalls grown by selective area molecular beam epitaxy.

Long-range response in halide perovskites

The Egger group has their expertise in crafting new theoretical methods for predicting functional properties of technologically relevant solar materials around room temperature with computer simulations. Their interest lies in the physical and chemical effects that occur on the small, in fact tiny scales, inside the materials: what keeps the atoms together? How do they move at room temperature? How is sunlight absorbed? And what is the potential the electrons "feel" inside a disordered crystal? In this quest they have recently discovered a paradoxical effect in the halide perovskites[6], which in recent years have become the most promising materials for a new generation of highly efficient solar cells.

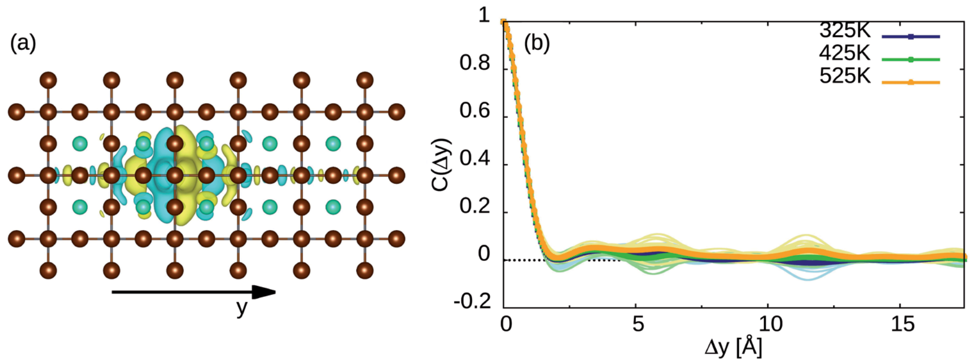


Fig. 4. (a) Illustration of the long-range effect in the halide perovskite crystal CsPbBr3 that is induced by displacing a single atom in the material. (b) Dynamically-shortened correlation in the disorder potential in CsPbBr3 due to the thermal motions of the ions in the crystal.

They showed that halide perovskites at around room temperature feature a long-range response in their properties when the crystal lattice is slightly modified by only a small perturbation in the position of a single atom. Such long-range effects are currently discussed to be one origin of the unusual crystalline dynamics of these materials, yet they seemingly stand in contrast to the outstanding solar absorber properties the halide perovskites are so famous for. The contradiction was resolved by the researchers discovering that there is "order in the disorder", namely that the long-range perturbations surprisingly are diminished once the entire sets of atoms in the crystals are allowed to undergo their thermal motion. Then, the correlations in the disorder potential, which are a measure for how far such perturbations are connected in space, vanish on the order of only one atomic bond. This is an important finding helping to understand better the microscopic origins that underlie the solar properties of perovskite and other types of energy materials.

[6] C. Gehrmann; D. A. Egger: Dynamic shortening of disorder potentials in anharmonic halide perovskites Nat. Commun., 3141 (2019)

Degradation mechanisms in organic solar cells probed with operando studies

Solar energy harvested with organic solar cells (OSCs) is considered as an alternative with promising potential for renewable and green energy sources due to the low costs, flexibility, solution processing, and large-scale fabrication of OSCs. For many years, increasing the power conversion efficiency (PCE) has been the main research direction of organic photovoltaics (OPVs). Now the champion PCE for single-junction OSCs has climbed up to around 18 %, which is quite close to the value of theoretical predictions. However, despite high PCE values reached, a poor device stability is preventing the real application of OSCs so far. Consequently, a better understanding of the degradation mechanism of OSCs is attracting more and more attention. The Müller-Buschbaum group used operando grazing-incidence small/wide-angle x-ray scattering (GISAXS/GIWAXS) characterizations to determine the correlation between the evolution of active layer morphology and the photovoltaic device performance (Fig. 5).

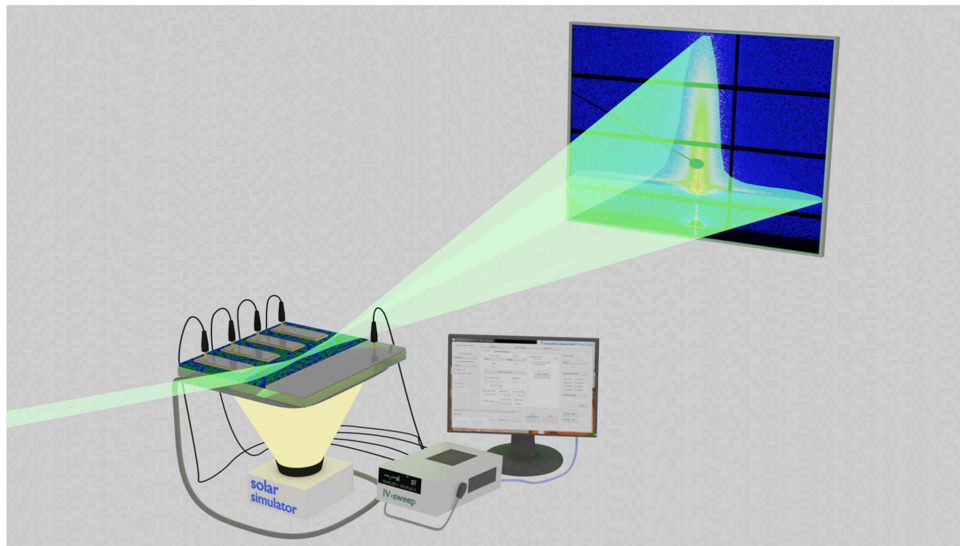


Fig. 5. Sketch of the operando experiments using real-time scattering experiments during the device operation to study morphological degradation mechanisms in solar cells.

Besides chemical degradation of the device materials, which is frequently attributed to a reaction with water or oxygen, physical degradation was found to arise mainly from the morphology deterioration of bulk heterojunction (BHJ) films [7,8]. Two major morphological degradation pathways were determined: A demixing-driven coarsening of inner structures and a mixing-driven loss of connectivity due to shrinkage of domains. The demixing-driven coarsening resulted in a decrease of the short circuit current of the devices, whereas the domain shrinkage caused an amplification of recombination and thereby a decrease in the fill factor [7].

Recent experiments indicated a higher complexity in the pathways of morphological degradation and thus the operation-driven morphology changes in BHJ devices were further explored. Solvent additives are widely used to modify the morphology of BHJ films to achieve a good interpenetrating network of donor/acceptor materials for improved exciton dissociation and charge transport. However, residual solvent additive in the final device resulted in a decay of the fill factor during the operation when the leftover solvent escaped from the device under vacuum conditions. Therefore, avoiding the presence of residual solvent in the final devices should be taken into consideration to avoid such degradation pathways. Moreover, different solvent additives were demonstrated to impact differently on the device stability and the evolution of crystalline grain sizes was codependent with the decay of open-circuit voltage [8]. Such studies contribute to the knowledge about fundamental processes in OSCs during operation and will thereby improve the lifetime of this promising technology for future solar energy harvesting.

[7] D. Yang, F. C. Löhrer, V. Körstgens, A. Schreiber, S. Bernstorff, J. M. Buriak, P. Müller-Buschbaum: In-operando study of the effects of solvent additives on the stability of organic solar cells based on PTB7-Th:PC71BM; ACS Energy Lett. 4, 464-470 (2019)

[8] D. Yang, F. C. Löhrer, V. Körstgens, A. Schreiber, B. Cao, S. Bernstorff, P. Müller-Buschbaum: In operando GISAXS and GIWAXS stability study of organic solar cells based on PffBT4T-2OD:PC71BM with and without solvent additive; Adv. Sci. 7, 2001117 (2020)

Charge transport in energy materials

The Oberhofer group focuses on the theoretical elucidation of charge transport in energy materials such as batteries and (metal-) organic semiconductors. Employing advanced electronic structure methods, to a large part developed in the group, the group was able to settle a long-standing mystery in the field of battery materials. Specifically, Lithium Titanium Oxide (LTO), which is a promising battery cathode material, has long been known to be electronically insulating in its pristine form, but shows appreciable conductivity when chemically treated in a reductive atmosphere. The Oberhofer group was able to show for the first time,[9] that this improvement is due to the formation of a type of quasi-particle known as small polarons. These are electrons, which localize, in this case on a single Ti atom, due to the polarization and deformation of their environment. The same work also demonstrated these polarons to be mobile (Fig. 6) thus explaining the observed increases in conductivity.

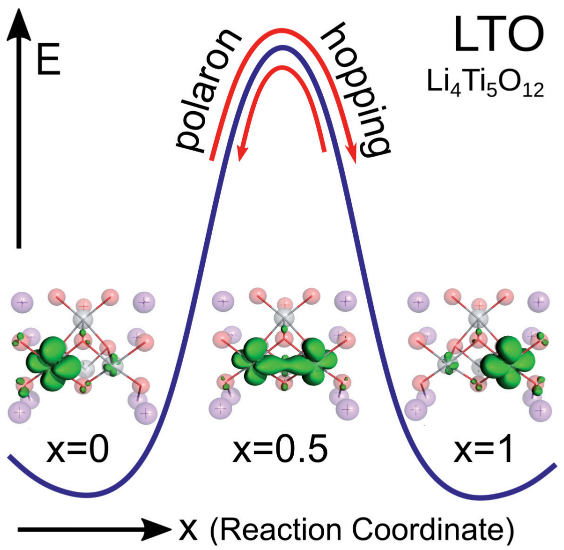


Fig. 6. Polaron hopping mechanism of electron conduction in an LTO battery cathode.

In a later work, the group then found that polarons are actually more stable near surface facets of LTO hinting at a possible mechanism of surface-mediated electrical conductivity. In a separate study,[10] the Oberhofer group also presented an improved approach to calculate conductivities in a different transport regime, where the charge carrying electrons (or indeed electron holes) are fully delocalized in the extended solid. Applying this approach to metal-organic framework (MOF) semiconductors, the Oberhofer group was able to identify a new and very promising Ruthenium-based triazolate MOF, to be investigated further in future experimental studies. Finally, the Oberhofer group also contributed a number of other methods for the study of charge transport in general. For ultra-fast transport, e.g. for molecules at surfaces, the group presented an improved approach to calculate the parameters determining the rates of transport. With a view on organic crystals, the group also developed a high accuracy force field allowing to estimate electronic polarization with the accuracy of an electronic structure code, yet at the greatly reduced computational cost of a simple matrix diagonalization.

[9] M. Kick, C. Grosu, M. Schuderer, C. Scheurer, H. Oberhofer, Mobile Small Polarons Qualitatively Explain Conductivity in Lithium Titanium Oxide Battery Electrodes, J. Phys. Chem. Lett. 11, 2535 (2020)

[10] C. Muschielok, H. Oberhofer, Aspects of Semiconductivity in Soft, Porous Metal-Organic Crystals, J. Chem. Phys. 151, 015102 (2019)

Joint Research Projects on Hydrogen and PtX

The TUM.Hydrogen and PtX Network and its partners are actively involved in several projects and activities. A selection of projects that are carried out in TUM co-operation or in collaboration with external partners is presented. Five interdisciplinary PtX projects are currently being carried out, which seeks to demonstrate the link between fundamental research and application.

Kopernikus-Project P2X
Research, validation and implementation of „Power-to-X“ concepts

KOPERNIKUS PROJEKTE P2X Die Zukunft unserer Energie

Website: **https://www.kopernikus-projekte.de**
Type: Project within the Kopernikus-Strategy of the BMBF
Funding: German Federal Ministry of Education and Research (BMBF)
Duration: 09/2019-08/2022

A reduction in critical platinum group materials as well as an improved efficiency of PEM water electrolyzers are the main objectives of the research project. In addition, a life cycle analysis (LCA) of the PEM electrolysis shows the impact of building and operating the PEM on several environmental impact categories. On a wider scale, the implementation of PEM electrolyzers in a European energy model is showing possible paths of sector coupling in Europe.

Within the Kopernikus-Project P2X, the **Chair of Technical Electrochemistry** (TEC) develops new materials and optimizes MEAs (membrane electrode assemblies) for the efficient production of high-pressure hydrogen via PEM water electrolysis. Initial studies within the project show that with today’s commercial catalyst materials, the required iridium loading on the anode of the electrolyzer is $\geq 0.5\ mg_{iridium}/cm^2$. For lower loadings, the catalyst layer becomes too thin and inhomogeneous, which results in a significantly lower performance. Consequently, new highly structured catalyst materials with low packing densities ($g_{iridium}/cm^3_{electrode}$) are developed that enable the fabrication of a thicker, homogeneous catalyst layer and, hence, a good performance even at low iridium loadings. Since a sufficiently long-term stability of these materials is essential to allow their implementation in larger PEM electrolyzer systems, accelerated stress tests are being developed to simulate PEM water electrolyzer operating conditions. A study based on commercial catalyst materials shows that frequent start-up and shut-down events can lead to a faster degradation rate. In the future, these test protocols will be applied to new catalyst materials to test and optimize their durability.

In the project, the synthesis gas is processed in a Fischer-Tropsch reactor to long-chain hydrocarbons, from which the desired product is formed in the downstream process. These and other plant options for the integrated production of different downstream products will be simulated to optimally link the process steps and adapt them for high production volumes. The Institute of Plant and Process Technology (APT) has already reached an important milestone in the power-to-fuel sub-project. In a combined process, CO_2 filtration from air, water and renewable electricity using high-temperature co-electrolysis allows the sustainable production of synthesis gas, which is then converted into synthetic fuel in further steps. The container-sized plant is now to be scaled up to a larger scale supported by simulations.

The Chair of Renewable and Sustainable Energy Systems (ENS) investigates the Life Cycle Analysis of such processes and develops a roadmap for market integration based on energy system modeling. Hereby the European electricity system is modeled, including the possibility of generating hydrogen with PEM electrolyzers. This provides the answer to the questions of how sector coupling might be achievable in the future and how and where the necessary increase in electricity generation will take place in the timeframe until 2050.

e2Fuels
Renewable low-emission fuels

e2Fuels Erneuerbare Emissionsarme Kraftstoffe

Type: Collaborative project: research initiative „Energiewende im Verkehr“.
Funding: German Federal Ministry of Economics and Energy (BMWi)
Duration: 10/2018-10/2021

The project e2Fuels investigates the storage of excess electricity in synthetic fuels. It focuses on optimized generation, adaptation of engines and demonstration. The aim is to investigate the production of hydrogen, natural gas/methanol and oxymethylene ether (OME). Those fuels are used in the transport sector as well as in stationary applications. This project is carried out in co-operation with 16 partners from industry and academia. Alongside the research mentioned above, the project focuses on OME in mobile applications, hydrogen and methane in industrial applications and alternative fuels for maritime systems.

The task of the **Chair of Energy Systems** (LES) is to model the production of synthetic fuels and to integrate them optimally into the German energy system. For this purpose, the entire path from the integration of renewable electricity to the platform chemicals hydrogen, methane and methanol is modelled thermochemically. The focus lies on the electrolysis and various synthesis routes. In order to achieve the highest levels of efficiency, perfect integration of heat and by-products is indispensable including consideration of plant flexibility. With the help of an optimization algorithm, the size of the buffer storage tanks, and the component size of the plant are optimized via application planning. In a model of the German/European energy system, interactions and synergy effects on other sectors are evaluated. This holistic approach promises a sustainable desig n to produce synthetic fuels.

In addition, LES co-ordinates the submodule „System Analytical Investigations“. Partner chairs at the TUM investigate the production of the extremely low-emission fuel polyoxymethylene-dimethyl-ethers and prepare a life cycle analysis for synthetic fuels. The Fraunhofer Institute and the ZSW Baden-Württemberg are investigating current and future developments in the key technology of electrolysis and CO_2 sources. In this project, the LES also co-ordinates the work packages Life Cycle Analysis, OME-production, projections into the future of PEM-Electrolysis and future sources of CO_2.

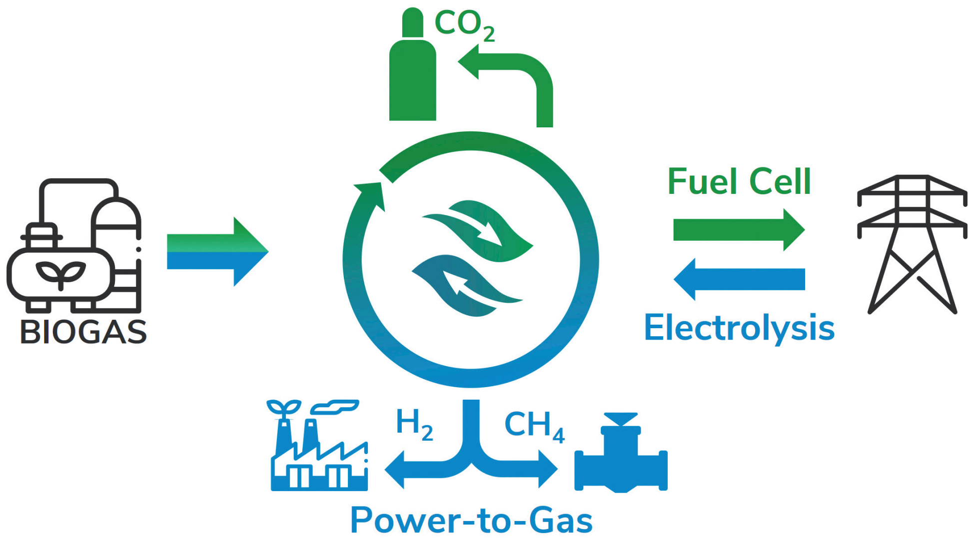
More TUM Partners: Institute of Internal Combustion Engines (LVK), Professorship Chemical Process Engineering (CTV), Professorship of Regenerative Energy Systems (RES)

BioCORE
Biogas COnversion with Reversible Electrolysis

Type: Validation funding VIP+ (high-tech strategy 2025)
Funding: German Federal Ministry of Education and Research (BMBF)
Duration: 09/2018-09/2021

Validation of a reversible, highly controlled, biogas-operated solid oxide cell system
A technology potentially allowing for very high exergetic efficiencies and therefore efficient power generation are solid oxide fuel cells (SOFCs). The expertise gained during previous SOFC projects is applied and combined with process design knowledge in the new project BioCORE. Since its beginning in 2018, it has focused on the development of a new, highly efficient fuel cell system to use biogas more efficiently from fermentation processes in a reversible system. Consequently, excess electrical energy from wind power and photovoltaics can be transferred into synthetic methane (SNG) and stored in the existing natural gas grid. Hence, the same system is capable of generating electricity from biogas and acting as a storage for fluctuating renewable electricity, both at very high efficiency. In the BioCORE project, this technology is to be validated as part of a prototype system, also to simplify scale up and to promote the commercialization of the process. After completion of the project the realization of a pilot plant with economically viable capacity will be addressed.

TUM Partner: Chair of Energy Systems (LES), Professorship of Regenerative Energy Systems (RES)



NaMoSyn
SustaiNable Mobility through Synthetic fuels

Nachhaltige Mobilität durch synthetische Kraftstoffe

Website: http://www.namosyn.de
Type: Third-party funded project with industrial participation
Funding: German Federal Ministry of Education and Research (BMBF)
Duration: 04/2019-03/2022

The aim of the project is to develop and test synthetic fuels for diesel and gasoline engines that can be produced and used sustainably. When using these fuels, significantly less greenhouse gases are released in total since the CO_2 emitted while driving was previously captured from other sources. In the collaborative research project with more than 30 partners from industry and academia, the production and use of synthetic fuels is studied in holistic fashion. For this purpose, a pilot plant for the production of OME, diesel fuels with a very clean combustion and sustainable production, e.g. built from renewable raw materials.

The **Professorship Chemical Process Engineering** (CTV) contributes by erecting a mini-plant for the production of oxymethylene ethers (short: OME), diesel fuels with a very clean combustion and produced sustainably, e.g. from renewable resources. The mini-plant is designed to follow an innovative process concept that was developed in-house during the last five years.

At the **Chair of Internal Combustion Engines** (LVK) sootless fuels for gasoline engines are investigated. Dimethyl carbonate (DMC) and methyl formate (MeFo) can be derived from green methanol and offer several benefits for engine use: high knock resistance, low NO_x formation and fast combustion make it possible to design high-efficiency spark-ignited engines. These potentials are demonstrated on a research engine and later transferred to a production engine by industry partners.

CleanTechCampus Garching

Contact:
Dr.-Ing. Annelies Vandersickel
annelies.vandersickel@tum.de
Chair of Energy Systems
& Energy Economy

Boltzmannstrasse 15
85748 Garching
Tel.: +49 89 289 16339

www.mse.tum.de/MSE

Sector-Coupled, Intertemporal Energy System Optimisation of Mixed-Use Areas: Concept and Tool Development Based on the Campus Garching of the Technical University of Munich

Motivation

More than 15.000 students and 3.500 employees at the Campus Garching of Technical University of Munich currently emit an average of approx. 2.5 t CO_2 per capita and year for the supply of electrical and thermal energy on site. Compared to the average annual total emissions per capita in Germany, which are currently just below 10 t CO_2 equivalent (European Environment Agency), the 2.5 t per year is a significant amount. In order to clearly reduce these emissions at Campus Garching in the coming years and thus contribute to the success of the Energiewende, a comprehensive transformation of the existing energy supply is required.

Goals

Universities provide ideal boundary conditions for sustainable transformations as a result of the combination of teaching, research and practical implementation, especially in the area of energy supply. The vision is therefore to establish the Campus Garching as a role model for a holistic energy transformation. In the context of the CleanTechCampus project, the foundations for this were established by analyzing a wide variety of energy supply concepts in detail. The next step is to implement the most promising solutions for transforming the energy supply on site by taking into account ecological, economic and innovative aspects. Fig. 1 presents selected opportunities that arise as a result of a sustainable transformation of the energy system at university sites.

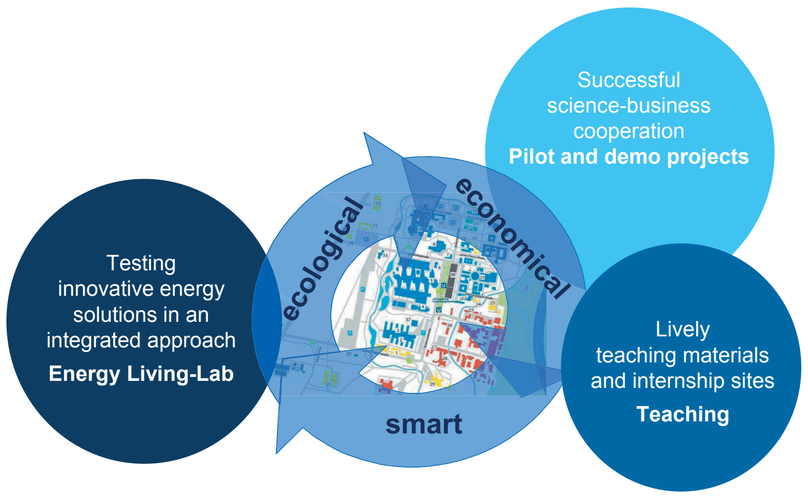


Fig. 1: Opportunities for a sustainable transformation of the energy supply at the Campus Garching

In the long term, this could lead to the creation of a lively Energy Living Lab on campus, where students and scientists work together on one of the most exciting and relevant research topics of the present and near future.

Baseline

Currently, about half of the campus' electricity demand is met on-site by a natural gas-fired Cheng Cycle plant, a gas turbine that can be operated flexibly as a result of optional steam injection. The remaining part of the electricity demand is purchased. The Cheng Cycle plant is a CHP plant (CHP: combined heating and power) that provides heat as well as electricity. Together with two gas boilers, which are located together with the Cheng Cycle plant in the heating center in the southwest of the campus (see Fig.2), the heat demand is covered on site all year round. The thermal energy is distributed from the heating center to the consumers by a district heating network. This network is currently operated at very high system temperatures, which means that the efficiencies of CHP plants are comparatively low and the heat losses are high due to the high temperature differences to the surroundings. In addition, the high system temperatures prevent an economical integration of renewable heat. Two waste heat sources with high thermal capacities, both of which are located directly on the campus, would be suitable for this purpose. One is waste heat from the water-cooled high-performance computer of the Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften (lrz) and the other is a deep geothermal hydrothermal reinjection well of Energie-Wende-Garching GmbH & Co. KG (EWG). The cooling demand of the campus is covered by building-specific cooling systems, mainly by smaller compression chillers. Only the buildings of the Faculty of Chemistry and Mechanical Engineering are each supplied with a larger, thermally driven absorption chiller.

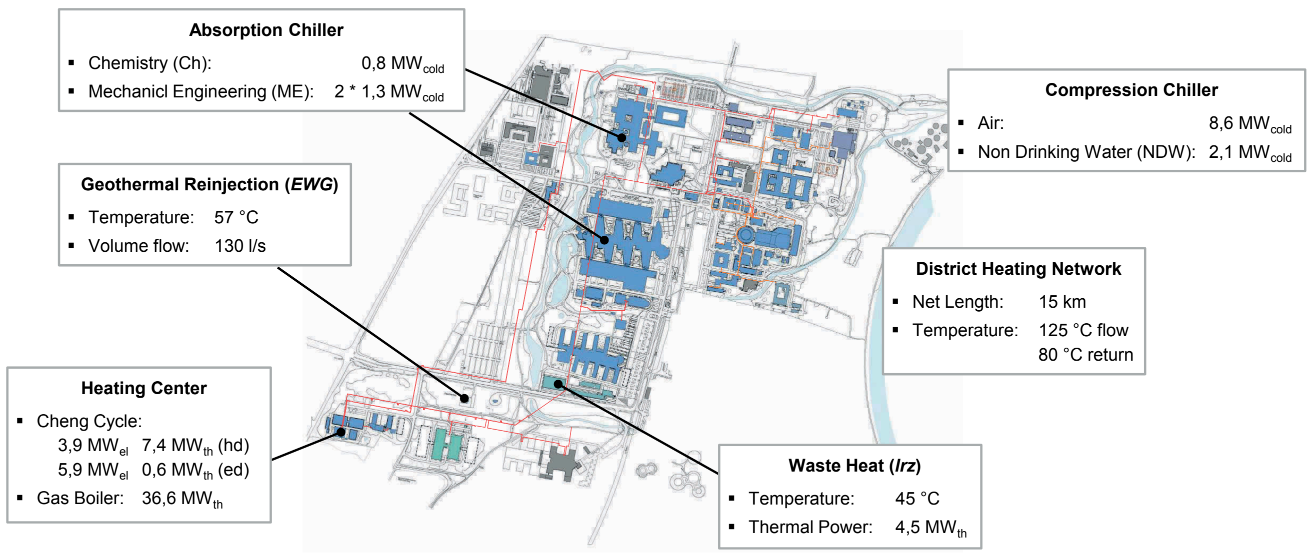


Fig. 2: Current energy supply system of the Campus Garching of the Technical University of Munich (el: electric; th: thermal; hd: heat driven; ed: electricity driven)

Project Implementation

In order to create holistic transformation pathways for the campus' energy system, the CleanTechCampus project involved an interdisciplinary team. This team consisted of the project-leading Chair of Energy Systems, the ZAE Bayern, the Chair of Renewable and Sustainable Energy Systems, the Control of Renewable Energies junior research group and the Center for Sustainable Building.

At the start of the project, all buildings on campus were inspected to capture information on the building envelope and technology in a comprehensive geographic information system (GIS) database. In addition, Building Information Modeling (BIM) models were created for the largest buildings on campus and the hydraulics of the existing district heating network and future expansion stages were modeled. These hydraulic analyses allow, for example, a well-founded evaluation of the extent to which pipelines in the existing district heating network will allow future reductions in network temperatures. Forecasts for electricity, heating and cooling demand were made up to 2040. For this purpose, historical consumption was analyzed, additional mobile measurements - in particular to record cooling consumption - were carried out, and the future development of the Campus Garching in terms of construction and personnel was taken into account.

The central aspect of the project was the implementation of sector-coupled, intertemporal energy system optimizations. For this purpose, the energy supply for the period from 2017 to 2040, divided into 5-year intervals, was optimized simultaneously for the electricity, heating and cooling sectors, whereby the coverage of the projected hourly energy demands must always be ensured. Fig. 3 provides an overview of the conducted energy system optimizations. Among other things, the existing energy system, different energy sources, numerous potentially installable energy conversion plants and storage technologies, energy policy framework conditions (electricity tax, EEG levies, individual grid charges) as well as strategic decision options, such as the reduction of heating network temperatures or the shutdown time of the Cheng Cycle plant, were taken into account. The open source optimization framework urbs (Chair of Renewable and Sustainable Energy Systems) was used as the optimization tool. The minimization of total costs over the entire period under consideration was defined as objective function, and compliance with CO_2 limits was specified as a mandatory constraint for most of the development scenarios considered.

By meeting all given boundary conditions, the results of the energy system optimizations are both an expansion planning of the most cost-effective energy conversion plants and storage technologies for the base years (2017, 2020, 2025, 2030, 2035, 2040) and an hourly deployment planning.

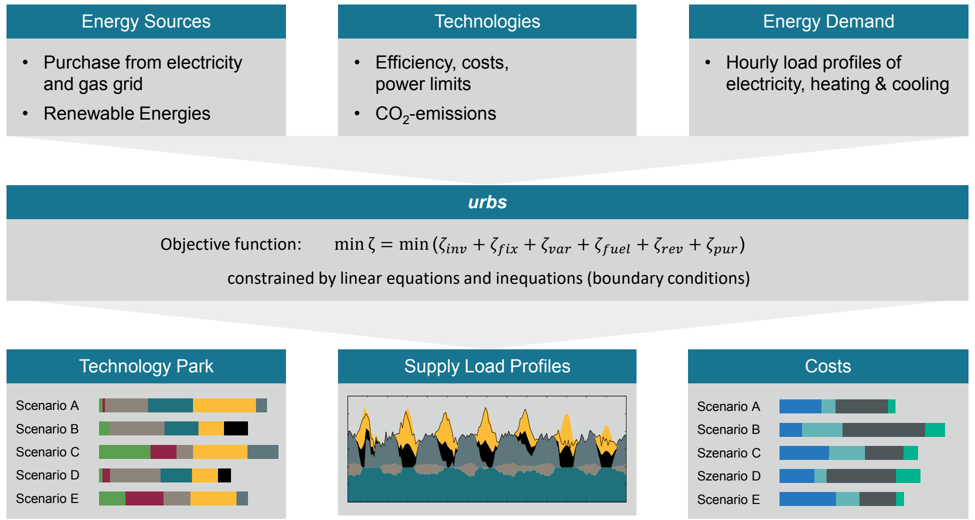


Fig. 3: Input and output of energy system optimisation (inv: investment; var: variable; rev: revision; pur: purchase)

At the Campus Garching, the annual electricity demand already exceeds the heating demand and in the future this ratio will most likely shift even more in the direction of electricity. In addition, the electricity demand is relatively evenly distributed over the year, whereas the heating demand fluctuates strongly depending on the season. The ratio of electricity to heat demand is crucial for the potential of natural gas powered CHP plants and electricity self-generation respectively. Pure natural gas power plants at district level cannot be operated economically due to the lower efficiencies of small plants compared to central large-scale power plants. Therefore, districts are dependent on coupling with other energy systems to reduce their greenhouse gas emissions, e.g. by purchasing electricity from the surrounding power grid. The extent of this dependence is influenced by various factors, such as the ratio of electricity to heat demand or the roof area available in the district for PV (photovoltaic) systems. From an economic point of view, a self-sufficient energy supply at district level is not very effective. For the Campus Garching, this means that complete climate neutrality is only possible by purchasing green electricity and/or biomethane. The purchase of green electricity was deliberately not included in the optimizations, as the target was an active contribution by the Campus Garching to the reduction of greenhouse gas emissions through its own energy supply facilities. The relative greenhouse gas reduction targets of the federal government of Germany compared to 1990 (status 2020) were set as CO_2 limits for the base years. A distinction was made here between absolute and area-specific CO_2 reduction targets. In the case of the latter, the projected increase in the net floor area of buildings for base years is taken into account. Fig. 4 shows the cost and CO_2 emission reductions for all scenarios examined compared to the standard reference scenario. In the reference case, the current existing plants are available to cover the energy demands, whereby the assumption was made that the Cheng Cycle plant will be replaced by gas engine CHP plants with an electrical output of 8 MW from 2025 and that the system temperatures of the district heating network will be lowered to 100 °C in the flow and 60 °C in the return in 2030. There were no CO_2 limits for the reference scenario. In almost all scenarios examined, both costs and CO_2 emissions are saved compared to the reference scenario. However, this requires investments for the transformation, so that the variable costs and ultimately also the total costs fall, in some cases considerably. A reduction in CO_2 emissions always goes hand in hand with this.

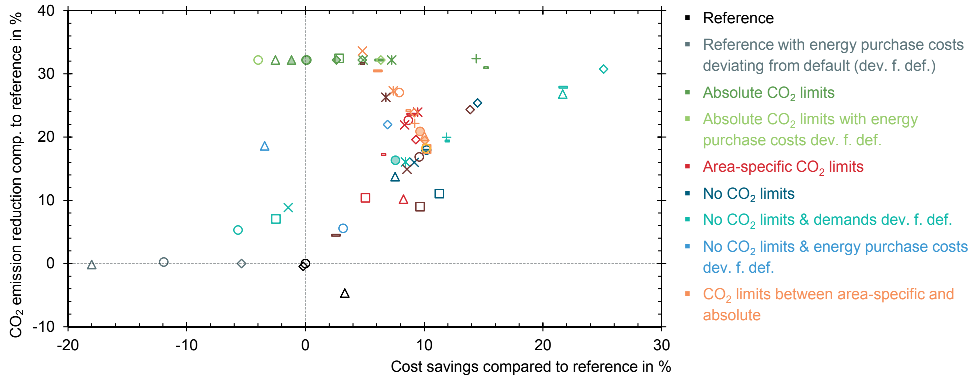


Fig. 4: Cost and CO_2 emission savings compared to the reference scenario for the observation period 2017 to 2040

The scenarios considered are assigned to different categories. The scenarios with absolute CO_2 limit reduction targets (green) all show almost identical cumulative emission reductions over the entire period. This demonstrates that these targets represent strict limits that are just met in each base year. Additional CO_2 reductions would result in higher overall costs. In the scenarios with area-specific CO_2 limits (red), on the other hand, the aggregate CO_2 savings vary. This is due to the fact that in certain base years these CO_2 targets are undercut for purely economic reasons. Both scenario categories have in common that the CO_2 savings in 2040 are 70% compared to 1990. They differ in the CO_2 targets only with regard to the consideration of the projected increase in land area.

If scenarios that differ from each other in only one boundary condition are compared, different trends can be seen. Fig. 5, for example, shows the effects of different district heating network temperatures on total costs and CO_2 emissions.

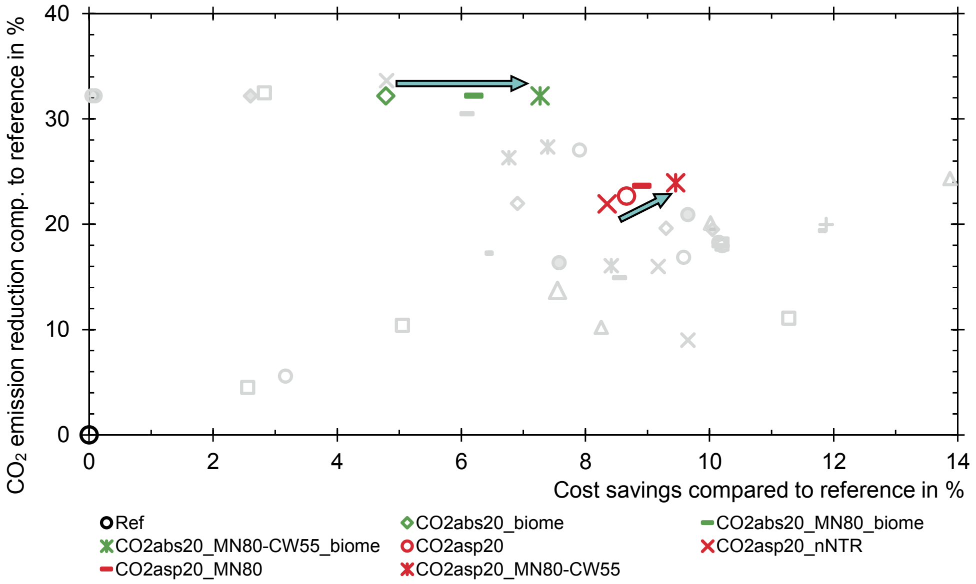


Fig. 5: Impact of reductions in district heating system temperatures on total costs and aggregated CO_2 savings (CO_2abs20: absolute CO_2 reduction targets from base year 2020 (default: from base year 2025); biome: optional biomethane purchase; MN80: reduction of flow temperature for the main network in 2030 to 80 °C (default: 100 °C); CW55: reduction of the flow temperature for the district heating network of the new Campus West development area to 55 °C (default: 80 °C); CO_2asp: area-specific CO_2 reduction targets; nNTR: no network temperature reductions in either district heating network)

For area-specific CO_2 reduction targets, both costs and CO_2 emissions decline with decreasing heating network temperatures, whereas for absolute CO_2 targets only costs fall due to the strict limits. However, the costs decrease significantly more for the same temperature reductions for scenarios with absolute CO_2 limits than for those with area-specific limits (see horizontal components of arrows in Fig. 5). This shows that reductions in district heating network temperatures significantly increase economic efficiency, especially for ambitious greenhouse gas reduction targets.

Fig. 6 depicts the annual electrical and thermal energy supply for the CO_2abs20_MN80_biome scenario, the middle of the three scenarios with absolute CO_2 targets from Fig. 5. For all base years, the area available for the installation of PV systems is used completely. Since this area is limited, PV modules are installed exclusively in an east-west orientation with an angle of inclination of 10°. Compared to a southward orientation, this has the advantage that significantly more PV modules can be installed on the same area due to less shading. The Cheng Cycle plant will be replaced by gas engine and biomass CHP plants from 2025. For the building of the Faculty of Mechanical Engineering, the construction of a highly efficient CCHP plant (CCHP: combined cooling, heating and power) is recommended, which enables the simultaneous supply of electricity, heating and cooling. The annual electricity supply exceeds the direct electricity demand (black lines), as additional electrical energy is needed to cover the cooling demand (not shown in Fig. 6) by means of compression chillers. The purchase of electrical energy from the surrounding electricity grid increases over years after the assumption of steadily decreasing CO_2 emission factors was made and the electrical self-generation in CHP plants is linked to a coinciding heat demand.

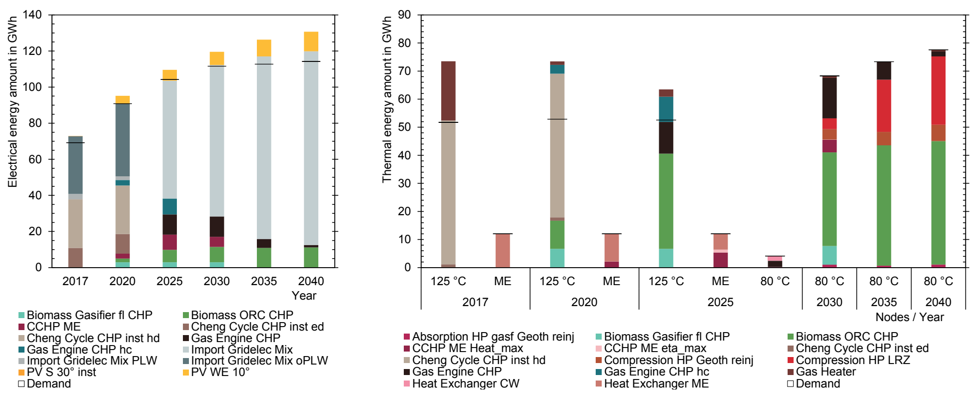


Fig. 6: Exemplary electrical (left) and thermal energy supply (right) for the scenario CO_2abs20_MN80_biome (fl: fluidised; ORC: Organic Rankine Cycle; inst: installed; hc: hot-cooled; oPLW: outside Peak Load Window; S: South; WE: West-East; HP: Heat Pump; gasf: gas-fired; Geoth reinj: Geothermal reinjection)

To model the heat supply, various supply nodes were integrated into the energy system model that differ in terms of their system temperatures. These nodes represent the main heating network (125 °C in the supply until 2025; 80 °C thereafter due to the scenario), the building of the Faculty of Mechanical Engineering (ME; 80 °C) and, from 2025, the district heating network of the new Campus West development area (80 °C). The extra node for the mechanical engineering building was set up because this building has a high demand for both heating and cooling and the integration of an innovative CCHP plant should be analyzed. This building can also be supplied with thermal energy from the main heating network (Heat Exchanger ME).

In the case of the heat supply of the main heating network node, the heat supply also exceeds the direct heat demand until 2025. This surplus heat is used on the one hand via a heat exchanger to supply the mechanical engineering node and on the other hand to drive absorption chillers. Due to the increasingly strict CO_2 limits over the base years, the use of solid biomass is steadily increasing. For efficiency reasons, the biomass here is fired only in CHP plants. Biomass heating plants with exclusive heat supply are not being built. From 2020 to 2030, the mechanical engineering building is partially supplied by a CCHP plant. From 2030 onwards, waste heat from lrz and EWG will be raised to the temperature level of 80 °C for the supply line by means of heat pumps. The lowest possible temperature levels are crucial for the future integration of waste heat, as the efficiency of the heat pumps and thus also the economic efficiency of the integration of waste heat decrease with increasing temperatures.

Apart from the system temperatures of the district heating networks, the areas available for PV or solar thermal energy on the Campus Garching also have a significant impact on costs and CO_2 emissions. Fig. 7 shows their influence.

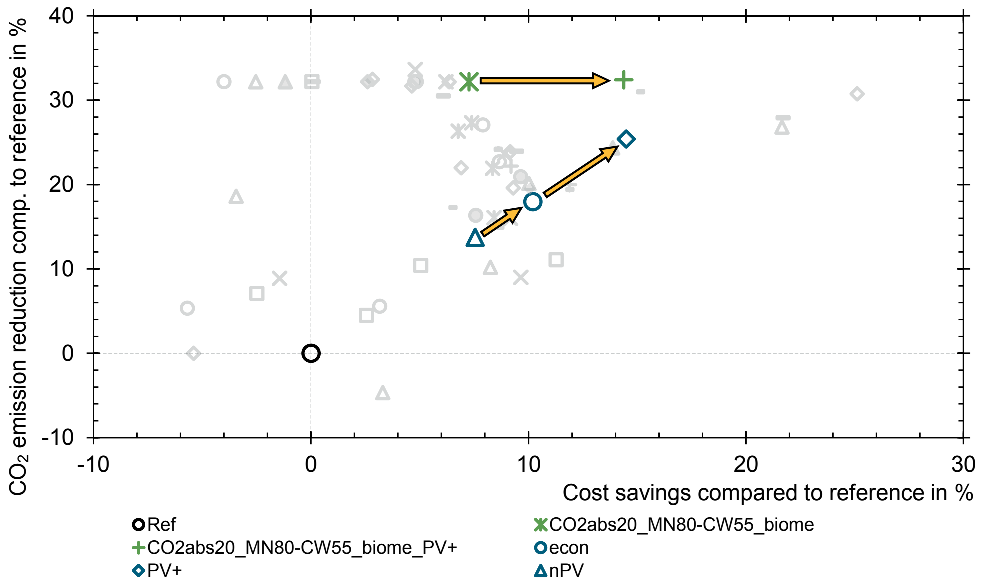


Fig. 7: Impact of area available for PV on total costs and aggregated CO_2 savings (econ: purely economic optimisation without specified CO_2 limits; PV+: complete unshaded roof area as potential area for PV (default: area for 4 MW_Peak,EW10° for 2017 and 50% of roof area of new buildings); nPV: no PV allowed)

Due to the cost-effective provision of electrical energy by PV and the temporal congruence with the electricity demand, in particular also the cooling demand, the available areas are always fully covered with PV modules in all scenarios considered. Solar thermal collectors are not used because of the congruence of areas with PV plants. For scenarios with area-specific CO_2 reduction targets, both costs and CO_2 emissions decrease with increasing potential area. As with the reduction of heating network temperatures, the more ambitious the CO_2 reduction targets, the more economical it is to build PV.

Summary and outlook

Within the CleanTechCampus project, numerous sector-coupled, intertemporal energy system optimisations were carried out (Schweiger et al. 2020). The methodology developed for this can also be transferred to energy systems of other mixed-use areas (Hermes et al. 2021). For the Campus Garching, it has been shown that under a wide range of conditions, considerable CO_2 savings can be achieved while reducing overall costs. This requires investments. Particularly recommended for the transformation of the current energy system into a sustainable one are:

- Installation of PV on all available roof surfaces
- Lowering the system temperatures of the district heating supply as ambitiously as possible
- Use of natural gas preferably only in CHP or CCHP plants; limited in time
- Use of biomass in CHP plants and/or purchase of biomethane with ambitious CO_2 reduction targets
- Establishment of comprehensive, intelligent energy monitoring and management as a prerequisite for efficient implementation

The prerequisite for a sustainable transformation of the energy system at the Campus Garching has been created with the establishment of numerous transformation pathways. To save CO_2 emissions and costs, their implementation is now required.

Publications

EEA: EEA greenhouse gases. data viewer. Available online at https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, checked on 6/24/2021.

A. Hermes, B. Schweiger, J.M. Kuckelkorn, W. Wedel, C. Matschi, M. Landerer, A. Vandersickel, H. Spliethoff: Leitfaden für die Energiesystemoptimierung zur Transformation komplexer Bestandsquartiere. Edited by Projektträger Jülich, Forschungszentrum Jülich GmbH. München. (2021)

B. Schweiger, A. Hermes, W. Wedel, C. Matschi, M. Landerer, K. Schönleber, A. Vandersickel, J.M. Kuckelkorn, L. Meyering, M. Radspieler, J. Röder,

I. Nemeth, H. Spliethoff: Entwicklung ganzheitlich optimierter, nachhaltiger und übertragbarer Energiekonzepte für komplexe Mischgebiete am Beispiel des TUM Campus Garching. CleanTechCampus. Abschlussbericht. Edited by Projektträger Jülich GmbH. München (2020)

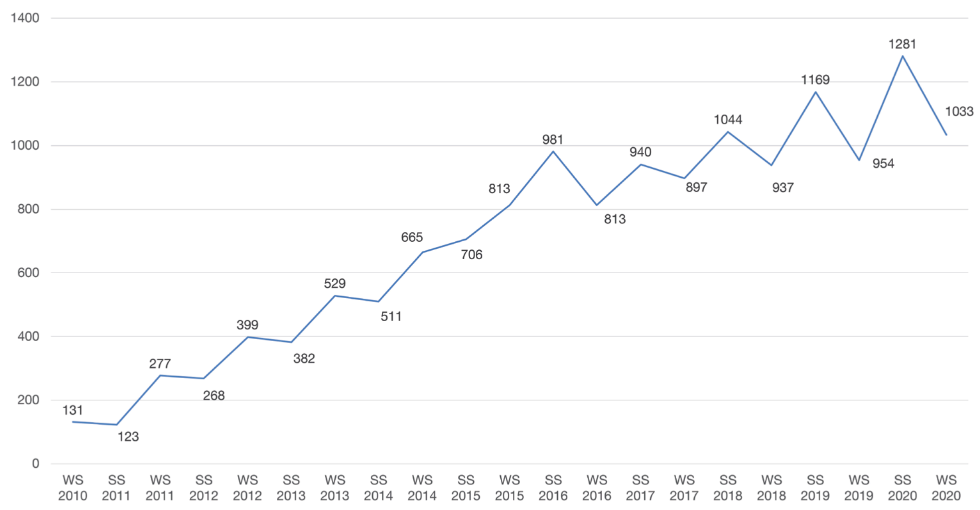
J. Dorfner: urbs: A linear optimisation model for distributed energy systems. Chair of Renewable and Sustainable Energy Systems, TUM. Available online at https://github.com/tum-ens/urbs, checked on 6/24/2021.

Andreas Battenberg / TUM

Facts & Figures

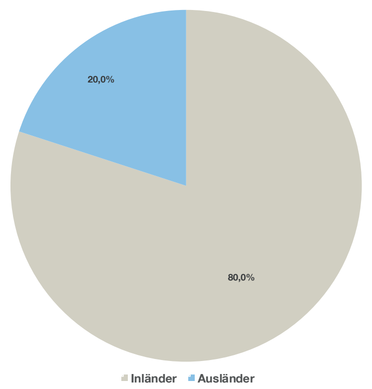
Facts & Figures

Students enrolled at MSE



State: 07.01.2021 / Source: TUMonline Studierendenmanagement

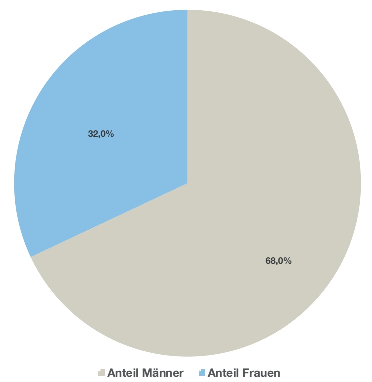
Proportion of international students



Relative share of international students per program	
studium MINT	13%
B.Sc. Engineering Science	19%
M.Sc. Ergonomics – Human Factors Engineering	12,5%
M.Sc. Industrial Biotechnology	27%
M.Sc. Materials Science & Engineering	65%

Stand: 07.01.2021 / Quelle: TUMonline Studierendenmanagement

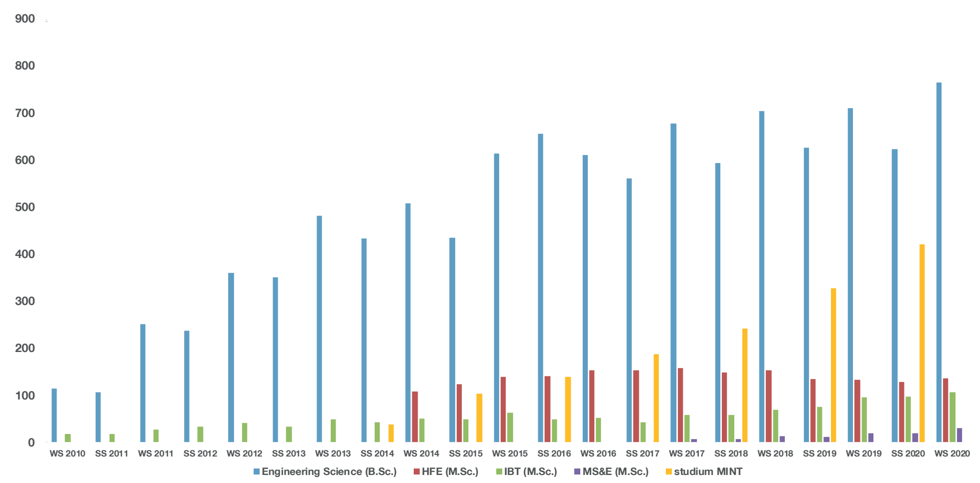
Gender proportion



Relative share of females per program	
studium MINT	39%
B.Sc. Engineering Science	25%
M.Sc. Ergonomics – Human Factors Engineering	60%
M.Sc. Industrial Biotechnology	49%
M.Sc. Materials Science & Engineering	21%

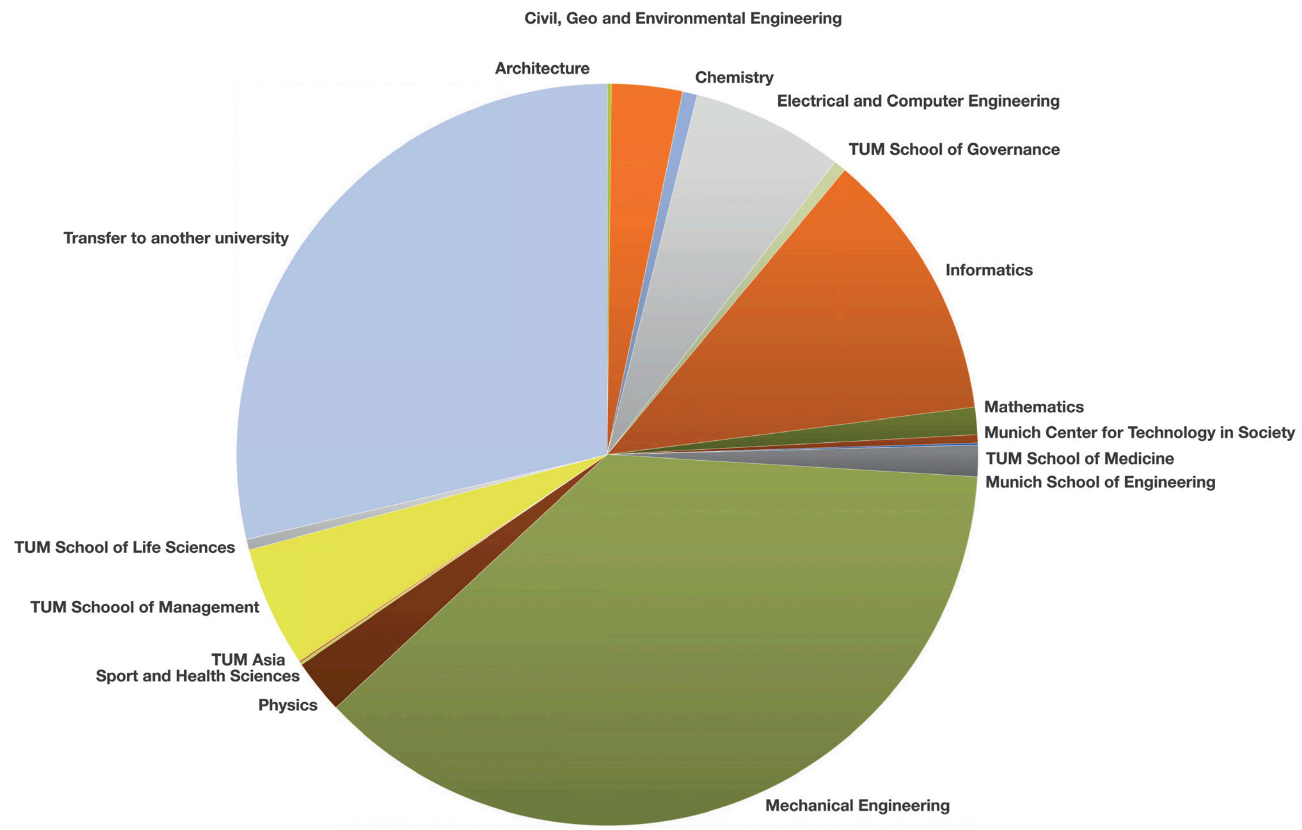
State: 07.01.2021 / Source: TUMonline Studierendenmanagement

Students per program



State: 07.01.2021 / Source: TUMonline Studierendenmanagement

Engineering Science: Subsequent master studies



State: 20.01.2020 / Source: TUMonline Studierendenmanagement

MSE Team

Heddergott / TUM

From left to right:

Mathilde Müller, Team Assistance (until 2019)
Cornelia Götze, Head of Academic Programs Office
Angela Brunnbauer, Assistance and Financial Accounting
Dr.-Ing. Christoph Wieland, General Manager
Petra Rau, Examination and Recognition Management B.Sc. Engineering Science
Daniel Hartenstein, Coordination B.Sc. Engineering Science (until 2019)
Prof. Dr.-Ing. Michael W. Gee, former Dean of Studies
Dr. Katja Block, International Affairs Delegate, Recognition Management Master Programs (until 2019)
Robert Graner, Quality Management Officer (until 2019)
Olga Marini, Coordination B.Sc. Engineering Science
Dr. Christiane Hamacher, Coordination Master Programs / MSE Graduate Center
Benjamin Farnbacher, Coordination studium MINT / Examination Board B.Sc. Engineering Science

Not in the picture:

Prof. Dr. Thomas Hamacher, Scientific Director
Prof. Dr. Phaedon-Stelios Koutsourelakis, Dean of Studies
Dr.-Ing. Petra Liedl, MSE Graduate Center

Andreas Battenberg / TUM

Publications

Selected Publications from Networks and Projects

TUM.Battery

[1] D. Schreiner, T. Zünd, F. J. Günter, L. Kraft, B. Stumper, F. Linsenmann, M. Schüßler, R. Wilhelm, A. Jossen, G. Reinhart, and H. A. Gasteiger: "Comparative Evaluation of LMR-NCM and NCA Cathode Active Materials in Multilayer Lithium-Ion Pouch Cells: Part I. Production, Electrode Characterization, and Formation", Journal of The Electrochemical Society 168 (3), 030507 (2021)

[2] L. Kraft, T. Zünd, D. Schreiner, R. Wilhelm, F. J. Günter, G. Reinhart, H. A. Gasteiger, and A. Jossen: "Comparative Evaluation of LMR-NCM and NCA Cathode Active Materials in Multilayer Lithium-Ion Pouch Cells: Part II. Rate Capability, Long-Term Stability, and Thermal Behavior", Journal of The Electrochemical Society 168 (2), 020537 (2021)

[3] S. Strangmüller, H. Eickhoff, D. Müller, W. Klein, G. Raudaschl-Sieber, H. Kirchhain, C. Sedlmeier, V. Baran, A. Senyshyn, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, and T. F. Fässler: „Fast ionic conductivity in the most lithium-rich phosphidosilicate Li14SiP6", Journal of the American Chemical Society, 141(36), 14200-14209 (2019)

[4] T. M. F. Restle, C. Sedlmeier, H. Kirchhain, W. Klein, G. Raudaschl-Sieber, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, T. F. Fässler: „Fast Lithium Ion Conduction in Lithium Phosphidoaluminates", Angewandte Chemie, 132(14), 5714-5723 (2020)

[5] L. Katzenmeier, S. Helmer, S. Braxmeier, E. Knobbe, and A. S. Bandarenka: „Properties of the Space Charge Layers Formed in Li-Ion Conducting Glass Ceramics", ACS Applied Materials and Interfaces, 13(4), 5853–5860 (2021)

[6] L. Katzenmeier, L. Carstensen, S. J. Schaper, P. Müller-Buschbaum, and A. S. Bandarenka: „Characterization and Quantification of Depletion and Accumulation Layers in Solid-State Li + -Conducting Electrolytes Using In Situ Spectroscopic Ellipsometry", Advanced Materials, 2100585

PtX

[1] V. Dieterich, A. Buttler, A. Hanel, H. Spliethoff, and S. Fendt: "Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review", Energy & Environmental Science (2020)

[2] K. Bareiß, C. de la Rua, M. Möckl, and T. Hamacher: "Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems", Applied Energy 237, 862-872 (2019)

[3] T. Burger, H. M. S. Augenstein, F. Hnyk, M. Döblinger, K. Köhler, and O. Hinrichsen: "Targeted Fe-Doping of Ni–Al Catalysts via the Surface Redox Reaction Technique for Unravelling its Promoter Effect in the CO 2 Methanation Reaction", ChemCatChem (2019)

[4] M. Bernt, A. Hartig-Weiß, M. F. Tovini, H. A. El-Sayed, C. Schramm, J. Schröter, C. Gebauer, and H. A. Gasteiger: "Current Challenges in Catalyst Development for PEM Water Electrolyzers", Chemie Ingenieur Technik 92 (1-2), 31-39 (2020)

[5] M. B. Jensen, D. Strübing, N. de Jonge, J. L. Nielsen, L. D. M. Ottosen, K. Koch, and M. V. W. Kofoed: "Stick or leave – Pushing methanogens to biofilm formation for ex situ biomethanation", Bioresource Technology 291, 121784 (2019)

NRG

[1] J. Fichtner, S. Watzele, B. Garlyyev, R. Kluge, F. Haimerl, H. El-Sayed, W.-J. Li, F. Maillard, L. Dubau, R. Chattot, J. Michalicka, J. Macak, W. Wang, D. Wang, T. Gigl, C. Hugenschmidt, and A. S. Bandarenka: "Tailoring the Oxygen Reduction Activity of Pt Nanoparticles through Surface Defects: A Simple Top-Down Approach", ACS Catal., vol. 10, no. 5, pp. 3131–3142 (2020)

[2] S. Strangmüller, H. Eickhoff, D. Müller, W. Klein, G. Raudaschl-Sieber, H. Kirchhain, C. Sedlmeier, V. Baran, A. Senyshyn, V. L. Deringer, L. van Wüllen, H. A. Gasteiger, and T. F. Fässler: "Fast Ionic Conductivity in the Most Lithium-Rich Phosphidosilicate Li14SiP6", J. Am. Chem. Soc., 141, 14200–14209 (2019)

[3] T. M. F. Restle, C. Sedlmeier, H. Kirchhain, W. Klein, G. Raudaschl-Sieber, V. L. Deringer, L. v. Wüllen, H. A. Gasteiger, and T. F. Fässler: "Fast Lithium Ion Conduction in Lithium Phosphidoaluminates", Angew. Chem. Int. Ed., vol. 59, no. 14, pp. 5665–5674 (2020)

[4] A. Birda, J. Reuss, and C. M. Hackl: "Synchronous optimal PWM for synchronous machines with highly operating point dependent magnetic anisotropy", IEEE Trans. Ind. Electron., vol. 68, no. 5, pp. 3760–3769 (2021)

[5] T. Burger, P. Donaubauer, and O. Hinrichsen: "On the kinetics of the co-methanation of CO and CO_2 on a co-precipitated Ni-Al catalyst", Applied Catalysis B: Environmental, vol. 282, p. 119408 (2021)

[6] L. K. Reb, M. Böhmer, B. Predeschly, S. Grott, C. L. Weindl, G. I. Ivandekic, R. Guo, C. Dreißigacker, R. Gernhäuser, A. Meyer, and P. Müller-Buschbaum: "Perovskite and Organic Solar Cells on a Rocket Flight", Joule, vol. 4, no. 9, pp. 1880–1892 (2020)

Network for Energy and Mobility Concepts

[1] D. Roy, S. Narayanaswamy, A. Proebstl and S. Chakraborty: "Optimal Scheduling for Active Cell Balancing", IEEE Real-Time Systems Symposium (RTSS), pp. 120-132 (2019)

[2] S. Narayanaswamy, S. Park, S. Steinhorst and S. Chakraborty: "Design Automation for Battery Systems", IEEE/ACM International Conference on Computer-Aided Design (ICCAD), pp. 1-7 (2018)

15 CoSES (6)

[1] T. Hamacher, V. Perić, and P. Kuhn: "Dialog der Systeme", Forschung-Das Magazin der DFG (2021)

[2] V. S. Perić, T. Hamacher, A. Mohapatra, F. Christange, D. Zinsmeister, P. Tzscheutschler, U. Wagner, C. Aigner, and R. Witzmann: „CoSES Laboratory for Combined Energy Systems At TU Munich", IEEE PES General Meeting (2020)

[3] V. Kleinschmidt, T. Hamacher, M. R. Hesamzadeh, and V. S. Perić: „Unlocking Flexibility in Multi-Energy Systems: A Literature Review", 17th International Conference on the European Energy Market (EEM) (2020)

[4] T. Licklederer, T. Hamacher, M. Kramer, and V. S. Perić: "Thermohydraulic model of Smart Thermal Grids with bidirectional power flow between prosumers", Energy, Volume 230 (2021)

[5] A. Behzadi, A. Arabkoohsar, and V. S. Perić: "Innovative hybrid solar-waste designs for cogeneration of heat and power, an effort for achieving maximum efficiency and renewable integration", Applied Thermal Engineering, 190 (2021)

[6] T. Kamal, M. Karabacak, V. S. Perić, S. Z. Hassan, and L. M. Fernández-Ramírez: „Novel Improved Adaptive Neuro-Fuzzy Control of Inverter and Supervisory Energy Management System of a Microgrid", Energies, 13(18), 4721 (2020)

GAB

[1] D. Bohnsack, M. Potten, D. Pfrang, P. Wolpert, and K. Zosseder: "Porosity-permeability relationship derived from Upper Jurasssic carbonate rock cores to assess the regional hydraulic matrix properties of the Malm reservoir in the South German Molasse Basin", Geothermal Energy 8, 12 (2020)

[2] F. Dawo, C. Wieland, and H. Spliethoff: "Kalina power plant part load modeling: Comparison of differ-ent approaches to model part load behavior and validation on real operating data", Energy 174 625-637 (2019)

[3] M. Drews, R. Seithel, A. Savvatis, T. Kohl, and H. Stollhofen: "A normal-faulting stress regime in the Bavarian Foreland Molasse Basin? New evidence from detailed analysis of leak-o and formation integrity tests in the greater Munich area", SE-Germany. Tectonophysics 755 1–9 (2019)

[4] S. Eyerer, C. Schifflechner, S. Hofbauer, W. Bauer, C. Wieland, and H. Spliethoff: "Combined heat and power from hydrothermal geothermal resources in Germany: An assessment of the potential", Renewable & Sustainable Energy Reviews, vol 120 (2020)

[5] F. Heine and F. Einsiedl: "Groundwater dating with dissolved organic radiocarbon: a promising approach in carbonate aquifers", Applied Geochemistry, vol. 125 (2020)

[6] C. Wieland, H. Spliethoff, and T. Baumann: "CO_2-neutral co-produced gas utilization for deep geothermal applications", Geothermics, 88, 101895 (2020)

MEMAP

[1] T. Licklederer, A. Capone, and M. Kramer: „Multi-Energy Management and Aggregation-Platform", 9th Energy Colloquium of the Munich School of Engineering - Shaping a Sustainable Energy Future (2019)

[2] D. Bytschkow, A. Capone, J. Mayer, M. Kramer, and T. Licklederer: "An OPC UA-based Energy Management Platform for Multi-Energy Prosumers in Districts", IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 1–5 (2019)

[3] MEMAP Research Group: „Nachhaltige Quartiere realisieren. Entwicklung einer Softwareumgebung für die Gebäude- und Sektorkopplung", Heizungsjournal, 1-2 (2020)

[4] MEMAP Research Group: „Werkzeuge für die Realisierung von nachhaltigen Quartieren – Regelung und Steuerung der Gebäude- und Sektorenkopplung", Netzpraxis (2020)

[5] MEMAP Research Group: „Werkzeuge für die Realisierung von nachhaltigen Quartieren – Softwareumgebung zur Regelung und Steuerung der Gebäude- und Sektorenkopplung", BWKenergie, 4-5 (2020)

[6] T. Licklederer, T. Hamacher, M. Kramer, and V. S. Perić: "Thermohydraulic model of Smart Thermal Grids with bidirectional power flow between prosumers", Energy, 230, 120825 (2021)

TUM.solar

[1] C.-M. Jiang, L. I. Wagner, M. K. Horton, J. Eichhorn, T. Rieth, V. F. Kunzelmann, M. Kraut, Y. Li, K. A. Persson, and I. D. Sharp: "Metastable Ta2N3 with Highly Tunable Electrical Conductivity via Oxygen Incorporation", Materials Horizons (2021)

[2] J. Fu, F. Wang, Y. Xiao, Y. Yao, C. Feng, L. Chang, C.-M. Jiang, V. F. Kunzelmann, Z. M. Wang, A. O. Govorov, I. D. Sharp, and Y. Li: "Identifying Performance-Limiting Deep Traps in Ta3N5 for Solar Water Splitting", ACS Catalysis 10, 10316 (2020)

[3] J. Winnerl, M. Kraut, S. Artmeier, and M. Stutzmann: „Selectively grown GaN nanowalls and nanogrids for photocatalysis: growth and optical properties", Nanoscale 11, 4578 (2019)

[4] C. Gehrmann and D. A. Egger: „Dynamic shortening of disorder potentials in anharmonic halide perovskites", Nat. Commun., 3141 (2019)

[5] D. Yang, F. C. Löhrer, V. Körstgens, A. Schreiber, S. Bernstorff, J. M. Buriak, and P. Müller-Buschbaum: "In-operando study of the effects of solvent additives on the stability of organic solar cells based on PTB7-Th:PC71BM", ACS Energy Lett. 4, 464-470 (2019)

[6] D. Yang, F. C. Löhrer, V. Körstgens, A. Schreiber, B. Cao, S. Bernstorff, and P. Müller-Buschbaum: "In operando GISAXS and GIWAXS stability study of organic solar cells based on PffBT4T-2OD:PC71BM with and without solvent additive", Adv. Sci. 7, 2001117 (2020)

Clean Tech Campus

[1] EEA: EEA greenhouse gases. data viewer. Available online at https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, checked on 6/24/2021.

[2] A. Hermes, B. Schweiger, J.M. Kuckelkorn, W. Wedel, C. Matschi, M. Landerer, A. Vandersickel, H. Spliethoff: Leitfaden für die Energiesystemoptimierung zur Transformation komplexer Bestandsquartiere. Edited by Projektträger Jülich, Forschungszentrum Jülich GmbH. München. (2021)

[3] B. Schweiger, A. Hermes, W. Wedel, C. Matschi, M. Landerer, K. Schönleber, A. Vandersickel, J.M. Kuckelkorn, L. Meyering, M. Radspieler, J. Röder,

[4] I. Nemeth, H. Spliethoff: Entwicklung ganzheitlich optimierter, nachhaltiger und übertragbarer Energiekonzepte für komplexe Mischgebiete am Beispiel desTUM Campus Garching. CleanTechCampus. Abschlussbericht. Edited by Projektträger Jülich GmbH. München (2020)

[5] J. Dorfner: urbs: A linear optimisation model for distributed energy systems. Chair of Renewable and Sustainable Energy Systems, TUM. Available online at https://github.com/tum-ens/urbs, checked on 6/24/2021.

Imprint

Publisher
Technische Universität München
Munich School of Engineering
Lichtenbergstr. 4a
85748 Garching

Editors
Prof. Dr. Thomas Hamacher
Dr.-Ing. Christoph Wieland
Dr.-Ing. Petra Liedl
Gabriele Semino

Coverbild:
Dr. Andreas Battenberg, TUM

Layout
Sonja Battenberg

September 2021