MSE

TUM

2017/2018

Munich School of Engineering

Annual Report

2017/2018

Munich School of Engineering

Annual Report

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Welcome

President’s Preface

Wolfgang A. Herrmann
President

Early this year, on January 26, 2019, the Commission on Growth, Structural Change and Employment, inaugurated by the German Federal Government, presented its exit strategy from solid fossil fuels. Its roadmap proposals outline a gradual phase out of lignite and hard coal by 2038. This marks the energy sector’s transition to a low-carbon economy that will foster the development of a sustainable energy supply. Naturally, this transition is associated with a multitude of research questions and challenges.
At the Technical University of Munich (TUM), our research can provide profound and sound responses to these challenges to support the transition with innovative developments in energy technology.

The Munich School of Engineering (MSE), established in 2010 as an Integrative Research Center, catalyzes energy research at TUM across all of its schools and departments. This interdisciplinary approach allows our scientists to conduct their research holistically, to develop their talents without barriers, and to access the support of other experts across disciplinary boundaries.

In 2017, the new Center for Energy and Information was inaugurated as the home of the Munich School of Engineering and its energy research. From the start, the building was planned as a research facility in its own right: Readily accessible controls allow researchers to actively optimize the cooling and heating infrastructure for research purposes. Innovative control concepts, encompassing state-of-the-art communication and information technology, make the facility a model for the energy optimized building design of the future. On its grounds, the building also offers four of the first public charging points for electric vehicles on the TUM Campus Garching.

In 2019, the Munich School of Engineering at the Center for Energy and Information will enhance its research complement with the WARR Hyperloop Team and the coordinating office of the e-Conversion Cluster of Excellence.

Strengthening its role as an interdisciplinary center, the Munich School of Engineering has expanded its academic programs portfolio to include the M.Sc. in Materials Science & Engineering. This top-notch, fundamental program demonstrates once more the high standards and quality that constitute TUM’s excellence. I am convinced that the Munich School of Engineering will continue to perform outstanding research and teaching, as well as to provide valuable scientific contributions to the research challenges of the future.

We gratefully acknowledge the invaluable support of the State of Bavaria in the construction of this new building and for the provision of resources to bring to fruition our vision of interdisciplinary research conjoined with cutting-edge Human-Centered Engineering. This pioneering philosophy is to extend the scope of traditional departments and will thus define the future of our university.

Prof. Dr. Dr. h.c. mult. Wolfgang A. Herrmann, President

Director’s Message

Thomas Hamacher
Director

A sustainable power supply is still the key for an overall sustainable development. Critical systems like water and food supply, which are challenged by climate change, can be managed if abundant energy is available at competitive prices. The transformation of the German energy system slowed down recently not at least due to the change in financing the roll-out of renewable energies. The former system based on feed-in tariffs was changed to auction system, which offers the opportunity to manage the build capacities. The coming years need to proof that the new system is more efficient. Public resistance slows down many projects such as the necessary build-up of new infrastructure like power lines connecting North- and South-Germany. The replacement of power lines by cables is significantly more expensive. This money could be spent much more efficient in other purposes. Making electricity to the major final energy carrier is under discussion although the transformation process did not start yet. Young people have made clear that they value new technology trends like digitisation a lot, but they also demand to keep the earth a liveable place even beyond the next fifty years.

This all makes energy research even more important. The development of concise pictures of a future energy system in close cooperation with the technology development reduces the uncertainty and helps to manage the transformation process.

Geothermal heat and power is becoming even more attractive in Bavaria in the recent years. The Geothermal-Alliance Bavaria is successfully established and is connecting the key players. The ambitious plans of Munich to supply a major fraction of the district heating system via geothermal heat is a lighthouse project which is quite visible in Germany.

Commissioning of the COSES lab will supply a unique platform for micro-grid research at TUM. Micro-grids are necessary to promote the use of electricity in new final energy sectors like the heating sector and this will help the integration of renewable energies. Beside this the COSES lab is well suited to investigate the supply of classical grid services like frequency and voltage control by decentral supply and demand units.

The Munich-School of Engineering did successfully graduate their first doctoral candidates. Especially in energy research it is of prime importance to make doctoral projects beyond the faculty limits.

Teaching at MSE is valuable and unique with high quality study programs. A perfect example for interdisciplinary study programs. The MINT program is offering orientation to those, which still have not made up their mind when entering the university. The popularity of the program proves that universities should have more contacts to schools to deliver at best during the time at the school the necessary orientation.

Prof. Dr. Thomas Hamacher, Director

Preamble, Dean of Studies

The Munich School of Engineering (MSE) has been established in 2010 with two main objectives. One of these objectives is to reinforce and synergize interdisciplinary research at TUM. The other objective is to enhance TUM´s teaching programs by specific programs, as response to current trends in technical education at the University level, and as anticipation of future developments.

Michael W. Gee
Dean of Studies

Future technological development and innovation have increasing impact on nearly all areas of life. Engineers that can cope with future challenges need to be exposed to interdisciplinary thinking and acting at the very roots of their education. Teaching programs at the undergraduate and at the graduate level at MSE have the purpose of meeting these needs.

The Bachelor's Program "Engineering Science" offers a challenging syllabus that emphasizes methodological and technological fundamental education. It meets the prerequisites of a wide range of different graduate programs and for a professional career in nearly any area of technological research, development or production. The program conveys natural and engineering sciences and thus offers students the flexibility of a later professional career at the interface between classical engineering disciplines or in natural sciences.

Bridging disciplines in applications is the objective of the three master's programs currently offered by MSE. The Master's Program "Industrial Biotechnology" addresses the need for preparing students to meet the interdisciplinary engineering challenges of bioprocesses and biomaterials. The Master's Program "Ergonomics – Human Factors Engineering" enables students to design and evaluate human-machine-interfaces in different technical domains. The novel Master program "Materials Science & Engineering" introduced in fall 2017 provides an interdisciplinary perspective on materials science, mathematical and numerical modeling of materials systems and engineering applications at highest standards. Its curricula involves contributions from the natural sciences, mathematics and computer sciences as well as all engineering departments at TUM.

Engineering education in the future will face the combined challenges of securing and further improving education quality, increasing the number of successful graduates, while competing with other education fields and alternative professional career paths for the brightest students. Outreach towards high-school graduates is a necessity, as there is no substitute to early familiarization and straightening preconceptions about engineering. MSE pursues the modern program studium MINT for aiding prospective students during their transition between school and University. studium MINT has seen extremely increasing attention and participation over its past years demonstrating the great need for bridging the school-university transition and the need for orientation in the field of MINT study programs.

Prof. Dr. Michael W. Gee, Dean of Studies

New Building for MSE

The Center for Energy and Information is now home of MSE

Energy research at the Technical University of Munich (TUM) now has a home of its own: On June 2017 the opening of the new Research Center for Energy and Information (ZEI) was officially celebrated. Built on the Garching Research Campus, scientists will perform interdisciplinary research on topics related to the energy transition. Dr. Ludwig Spaenle, the former Bavarian minister of science, said: “In the interests of a future-ready and sustainable energy supply, energy research is a key field of activity under Bavaria’s research and technology policy. I’m delighted that TUM has now opened the Center for Energy and Information. As one of the two top locations for interdisciplinary energy research in Bavaria, TUM now has a state-of-the art research center that provides a visible address for this important field of future activity. To create excellent conditions for scientists, we are providing 17 million euros in funding for the new building from the Bavarian energy research program.”

Facts and figures:

- 240 m² Workshop Area
- 400 m² Laboratory as shared facilities in energy research
- 252 m² Technical Laboratory for CoSES
- Building as Experimental Facility with its Concrete Core Cooling

The existing laboratories are operated as shared facilities accessible for researchers from different faculties and institutes to pursue high-level research in a modern and agile research facility. Dedicated topics are Batteries and PV as well as the sector-coupling, which is found in the technical laboratory for the Center for Combined Smart Energy Systems (CoSES). This Center integrates the building, its PV-Installation as well as the charging points outside the building into a unique experimental facility.

Both pictures: U. Benz / TUM

Students

Students

Studying at MSE

The demand for scientists able to co-operate beyond the borders of their traditional scientific disciplines is growing steadily. 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 for preparing for and orientating 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 programs in engineering. The program's target group are talented individuals with both interest in mathematics and natural science subjects who do not yet want to specialize concerning their academic and professional careers 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 with the opportunity to acquire a differentiated discipline-specific specialization, ranging from the natural sciences and mathematics to informatics.

Our graduates are thus perfectly equipped for solving complex problems across the entire range of the engineering sciences and its interfaces with the natural sciences. Arguably, it is 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 meet these challenges of tomorrow.

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Intention and focus

The B.Sc. ES prepares students for a steadily increasing diversity 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, the natural sciences and the life sciences. Consistently bilingual (approx. 50% German / 50% English), this intensive study program comprises 210 ECTS points instead of the usual 180 points and presents a challenging yet intellectually 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, the natural sciences and engineering is 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. Basically, the interviews test applicants' aptitude in mathematics and science subjects, in problem-solving and logical thinking, and their command of English.

Our freshmen at the Semestereinführungstag 2017

Nothdurft / FSMSE

Structure and profile

During the first two years of the program, students acquire the fundamentals of general engineering science, physics, chemistry, mathematics and computer science. The respective lectures and lab courses were specially developed for the B.Sc. ES and are attended exclusively by the program's students. Some of these lectures are consistently held in English, thereby underscoring both the program's and TUM's international orientation.

Additional coursework in interdisciplinary subjects supplements the curriculum: students are free to choose courses and workshops in the humanities and the social sciences; courses in English for specific purposes; and workshops on scientific methods and soft skills.

As a distinctive feature of the B.Sc. ES, students have the opportunity of taking 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 internship offers students the possibility of gaining first-hand experience of 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.

True to the program's interdisciplinarity, students have a wide array of academic fields to choose from in finding a topic for their bachelor's theses: 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
- 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)

J. Hofmann / TUM

Graduates of the B.Sc. ES at the Tag der MSE 2018

Master's Program Human Factors Engineering

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Modern technical products and processes feature a number of desired attributes: they have to be easy and convenient to use, and they need to efficiently support 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 the comfort, safety and health aspects of the technology they use.

It is clear that no scientific discipline can expect to be able to deal with this complex interplay of seemingly opposing requirements alone. Knowledge and insight from science, engineering and the humanities need to come together.

MSE is meeting this demand by offering the interdisciplinary Master's Program Ergonomics – Human Factors Engineering (HFE) that qualifies students for a transition to a doctoral program, or for careers in industry within the field of human factors engineering.

After graduation, HFE graduates are specialists in the design, implementation and evaluation of future concepts for man-machine interaction in the 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.

This master's program is the result of the close cooperation between the departments: Architecture, Mechanical Engineering, Electrical and Computer Engineering, Informatics and Sport and Health Sciences.

The Master's Program HFE is attracting an increasing number of students from TUM as well as from external universities both in Germany and abroad. There are currently 130 students registered in the program.

In the research field, graduates of this program are in demand as experts who can take the above-mentioned development and testing methods to the next level and who possess the skills to address research topics on man-machine interaction across technical domains (e.g. cooperative adaptive systems in production mobility). Our training teaches them how to put together and coordinate interdisciplinary research teams to produce an efficient and productive working climate.

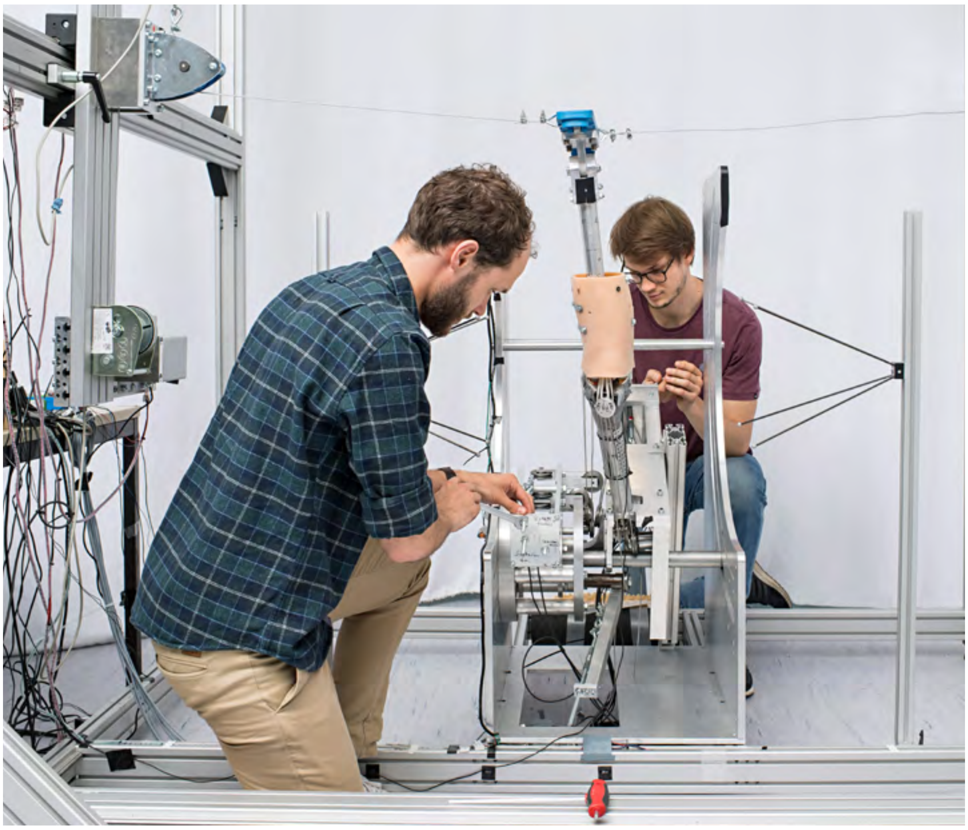
This includes activities in the following areas

- 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 that have 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 science 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 120 ECTS points 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 it ends with the master's thesis.



Testing bench for knee injuries

U. Benz / TUM

Master’s Program Materials Science and Engineering

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Technological developments are only possible with the knowledge, selection, description and characterization of materials. Therein, as in many other fields, developments show an increasing mutual perfusion of the natural/life sciences and engineering, especially in the field of technologically interdisciplinary topics such as the materials science and corresponding mathematical and numerical modeling. Thus, modern education in engineering is faced with the challenge of respecting classical disciplines while also including and representing interdisciplinary aspects. At the same time, the development of novel and composite materials opens up great potential for lighter, more energy-efficient, more environmentally friendly and safe construction in all engineering applications. The special knowledge of the properties of materials, their characterization, description by means of mathematical models, as well as monitoring and assessment, is therefore of elementary importance 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.

Aside of the disciplinary education at master level, 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 the economic and research environment in Germany, and particularly in Bavaria. It connects to the successful bachelor’s program Engineering Science, 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 a career in science and research are given the opportunity to extend their education both in materials as well as 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 the basic engineering disciplines, and the ability to make predictions based on numerical calculations and simulation methods. Here, “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 towards predictive simulations, i.e. prediction by simulation with a quantitative statement about prediction reliability that is currently taking place in engineering sciences, must be reflected in engineering education. With this program we embrace this development and emphasize the teaching of basic probability theory, probabilistic considerations and methods in the various disciplines. Interdisciplinarity is essential in research, which is reflected in the tailored curricula spanning involvement from the physics, chemistry, mathematics, computer science, life sciences and all engineering departments at TUM. This supplies the opportunity to deepen education in materials research without neglecting the fundamental engineering sciences. Furthermore, an Advanced Research Internship, characterized by close mentoring and supervision in customized courses in which scientific reading and writing is fostered, is an essential part 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 years, the production of bulk chemical products and fuels is also increasing. The demand for specialists in the field of industrial biotechnology who can work across a number of disciplines and have a broad range of expert knowledge in bioscience and process engineering is continually rising. MSE is meeting this increased demand by offering the interdisciplinary Master's Program Industrial Biotechnology (IBT). The Master's Program IBT first started in 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 74 students registered in the program.

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Study program profile

The IBT is aimed 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 work 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 are taught the fundamentals of process engineering.

After learning the interdisciplinary fundamentals, students receive specialized training in the second and third semesters in the following four key areas

- 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 freely choose a fourth field of specialization, having the opportunity to select courses that are of interest to them from the program offered by TUM or another university.

In the fourth semester, students complete a master's thesis. 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 Technical University of Munich who is involved in the study program.

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

After graduation the students consider themselves very well prepared to work in both, biotechnology as well as engineering and their job opportunities are excellent in research and industry. The number of applicants and students is growing steadily since the introduction of the study program in 2010. The study program qualifies graduates for 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 within 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, unique in the international academic landscape, offers researchers access to new biocatalysts and bio-products and provides 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.

Maslak / TUM

Students within the internship

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 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.

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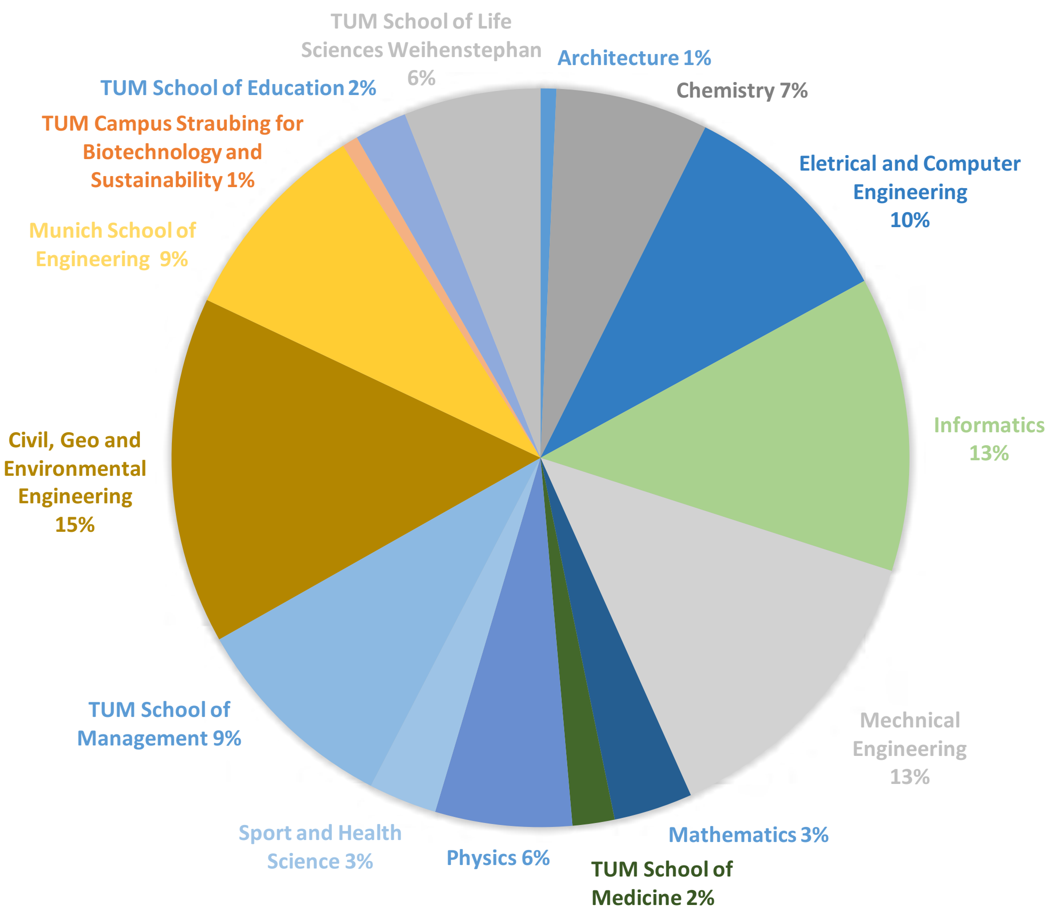


■ **Follow up: the TUM faculties where studium MINT participants enroll after the orientation semester**

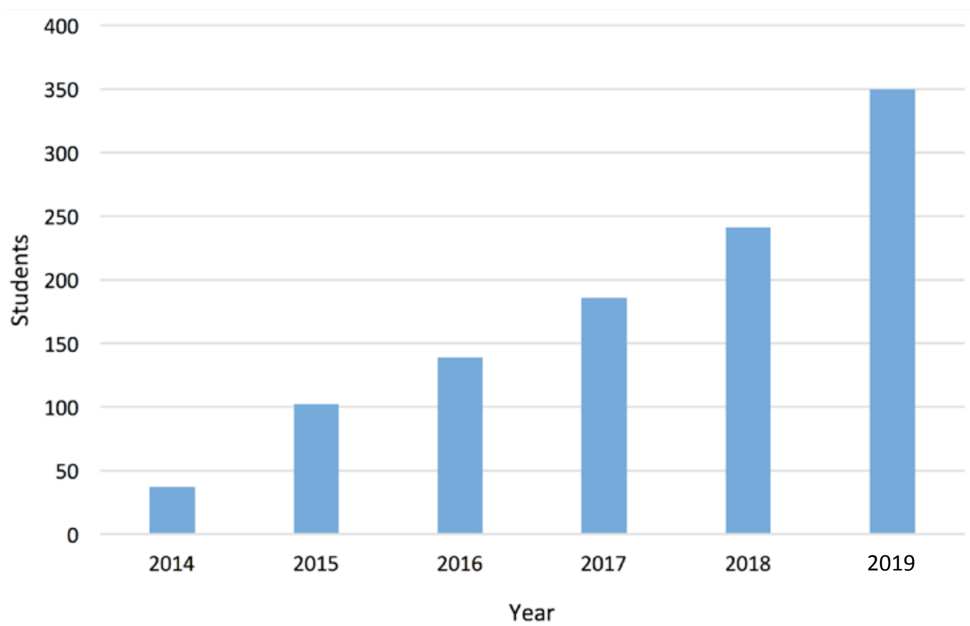
Institutions involved in studium MINT teaching

- 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)

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 245 in 2018. The current state of applicants allows to approximate numbers of 350 enrolled students for 2019.



Student’s voices

“The orientation semester and the broad range of available lectures not only facilitate my search for the right study program, but in particular provide a seamless transfer from school into university.”

Julia Aulbach (now studying Chemical Engineering at TUM)

“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 have a lot personal contacts already at the beginning of my bachelor’s program. Also the academic procedures like lectures, exercises, homework are familiar to me as well as the premises at Research Campus Garching.
All in all I keep studium MINT in mind as a great experience!”

Johanna Gebhard (now studying Engineering Science)

Students presenting their prototypes developed in MakerSpace: an ergonomic measuring doll for classrooms, a postbox with e-mail-service, a binary clock.

Farnbacher / TUM

MSE Student Council

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The Student Council of the Munich School of Engineering (Fachschaft MSE) was founded in December 2010 and represents the approximately 1000 students of MSE.. In addition, the Fachschaft MSE also represents the students of the orientation program “studium MINT”.

The work of the Fachschaft MSE can be separated into three main areas: The organization of events, the continuous improvement of study conditions, and student representation. All participation is on a voluntary base. 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 new heads of the student council and of the Fachschaft sections get elected by all MSE students. Currently, we have eight sections: Freshmen, Evaluation & Cooperation, Finances, IT, PR, Events, Scripts and University Politics. Beyond this, the Fachschaft tries to provide a broad platform, such that every student can work on a project for the MSE students if they want to, even if they aren’t elected in an official position.

Events These are some of the events the Fachschaft MSE has organized in the last year:

- Freshmen days: Each semester, about 250-300 new students start their studies at the Munich School of Engineering. The Freshmen Section organizes two days with all kinds of games for students of every program, so that they can get to know the city and their new fellow students. Furthermore, a brochure with numerous important information and tips about the city and the university life was created for students that begin studying at MSE. This brochure is continuously updated.

- Regular get-together events (Stammtisch): Once a month, the Events Section arranges a get-together for all MSE students. A newer addition are regular board game nights at our campus in Garching-Hochbrück, where the Fachschaft MSE provides snacks, drinks, and board games. It has turned out that both events are especially helpful for strengthening the connection between students in different programs and across the 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 have the possibility to get to know each other and the work of the student council.

- Other events: In 2018, we have also organized a semester opening party, our annual Christmas party and summer fair, a skiing day, as well as MSEating, where students get to know each other by preparing a meal together in a group of randomly selected peers.

Improvement of study conditions The Fachschaft MSE continuously tries to improve study conditions by providing scripts for all lectures, evaluating the lectures, and by passing on problems or ideas to the academic programs office. In 2018, we also started peer mentoring for the B.Sc. program: Here, students can ask peer mentors (students in a higher year) for advice concerning their further studies. Finally, we take care of the TUM premises at the business campus in Garching-Hochbrück, including the student lounge Quantum. We host a cloud where students can 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 their evaluation results, to reward high- quality teaching at MSE.

Student representation Via e-mail, phone, coming by the office or to the regular Fachschaft meetings: Every MSE student can raise issues that are important to them when contacting the Fachschaft MSE. 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 TUM (Fachschaftenrat). We thus have the ambition to solve problems as fast as possible. The Fachschaft MSE was actively involved in the reform of the B.Sc. program and is always heard when programs at MSE are to be changed. In addition, the Fachschaft MSE is 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.

Members of the Student Council

Tröbs / FSMSE

Diversity and International Affairs

The Munich School of Engineering (MSE) strives for diversity among students in terms of gender and international background in order to ensure equal opportunities.

Students of all nationalities have been welcomed since MSE was founded.
The introduction of attractive interdisciplinary programs has more than tripled the proportion of international students between the winter semesters 2010/11 and 2018/19 (from 5% up to 18%).

Furthermore, the proportion of female students at MSE has risen from 22% to 33% over the same period of time. In particular, the master's programs with a consistently high proportion of women (approx. 50%) are outstanding examples of women in MINT subjects.

At the beginning of 2018, two female bachelor students of MSE were able to be admitted to the international career network Femtec.

Through exchange programs such as Erasmus+, TUMexchange, ATHENS and further possibilities for grants, a wide variety of opportunities is open for students to obtain international experience.

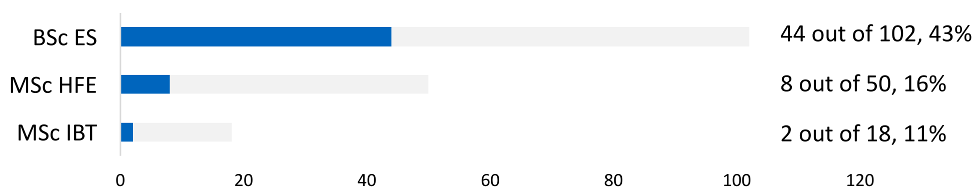
The centrally managed program TUMexchange comprises academic exchanges with selected universities from 26 countries outside the EU, while Erasmus+ supports study stays and internships within Europe. MSE has bilateral Erasmus+ agreements with renowned universities, for instance Danmarks Tekniske Universitet, École Polytechnique and ETH Zürich.

Increasing numbers of MSE students take advantage of the benefits of these opportunities and gain valuable study experience abroad (2015/16 62 students, 2016/17 66 students, 2017/18 73 students).

In 2017/18 MSE students traveled worldwide to 25 destinations and represented MSE at our partner universities.

Outgoing students by study program

Graduates academic year 2017/18 with one or more participations in mobility activities



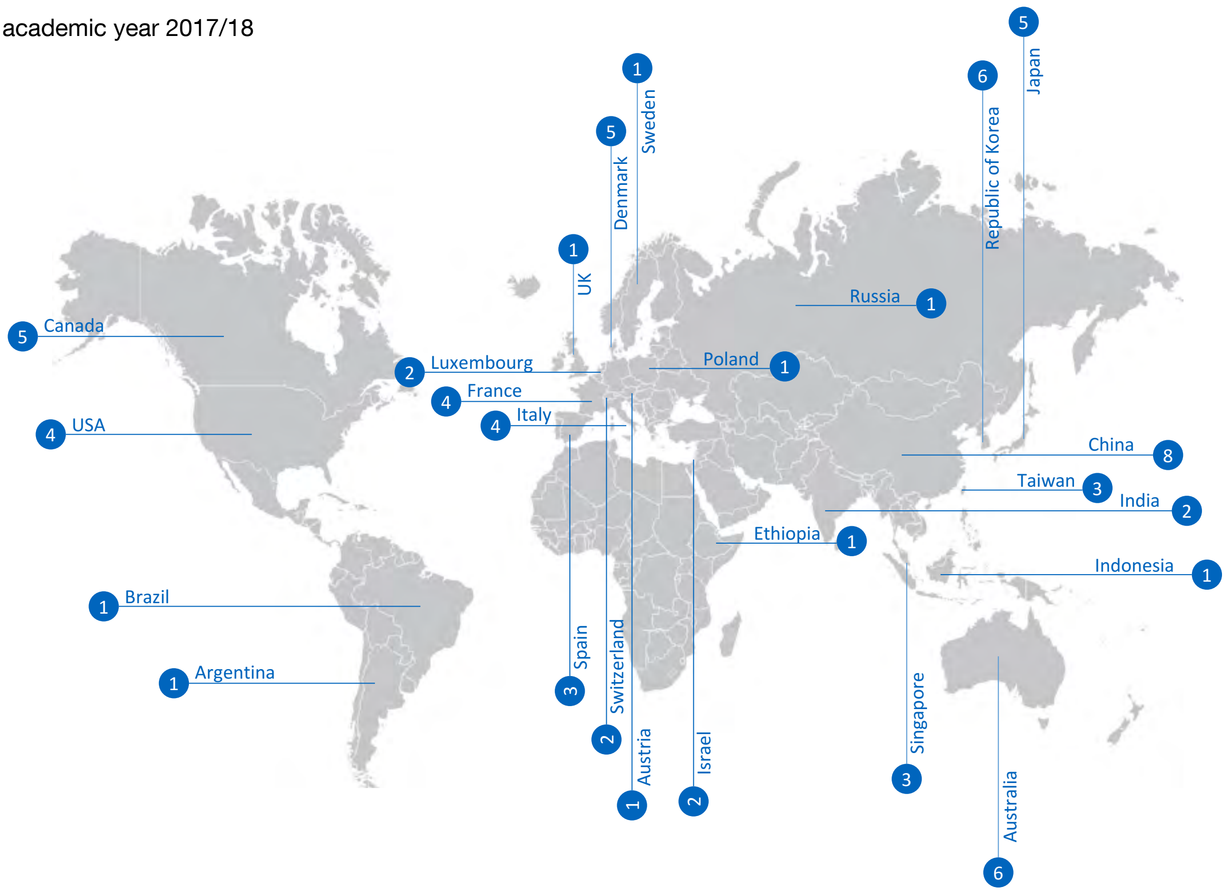
Outgoing students by mobility program

all study programs

ERASMUS		
	2015/16	17
	2016/17	23
	2017/18	20
TUM Exchange		
	2015/16	35
	2016/17	33
	2017/18	38
Other programs		
	2015/16	10
	2016/17	10
	2017/18	15

Outgoing students by destination

academic year 2017/18



Research Centers

Research Centers

TUM.Battery Network

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was initiated in 2018 by leading TUM researchers in the field of battery research. It is an interdisciplinary platform with currently 12 research groups, among them 8 chairs in 5 different TUM faculties and further research centers. One of the objectives is to bring together the expertise of the participating research groups and create a space for interdisciplinary exchange and networking.

In a first step, we have pooled TUM's expertise, which is now displayed on an appealing web page. The new common website presents all participating partners, their expertise and contributions to the battery research field:
https://www.mse.tum.de/battery/

Motivation for research

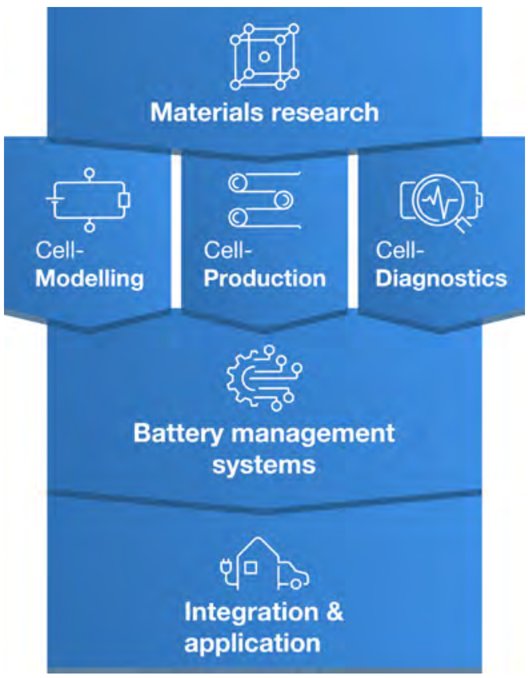
The main objective of TUM.Battery is to provide a platform for scientific exchange and networking amongst the researchers at TUM who are working on different aspects of battery research both in engineering and the natural sciences. Furthermore, the TUM.Battery website combines information and updates of the individual partners together with news of the TUM.Battery activities as part of the MSE homepage.

Members of the different chairs on post-graduate level come together and their scope is to present the battery research at TUM to other researchers, industrial partners and wider audiences. The network provides also a great opportunity for young researchers, Ph.D. students in particular, to network with members of other faculties.

Interdisciplinarity matters

Based on a strong interdisciplinary network, ranging from the fundamental physical properties of novel battery materials in the physics department and material synthesis in the chemistry department, all the way to full cell operations in the mechanical engineering department, the entire spectrum of battery research is represented.

The figure on the right shows the different steps from research to application, according to which the different researchers are integrated into TUM.Battery.



Introduction of selected participants

Materials research

Prof. Dr. Fässler and his Chair of Inorganic Chemistry with Focus on Novel Materials develop novel battery materials with special emphasis on anode materials as well as ion conductors for their usage in all-solid-state batteries. Beside the chemical syntheses the emphasis is put on the structural characterization.

Prof. Dr. Reuter and his Chair for Theoretical Chemistry take a more fundamental approach based on atomistic multi-scale material models with the goal of predictive quality simulations leading to an improved understanding of ion conductivity, material stability and interface resistances.

Modelling

In a next step, models for the chemophysical interaction of the different materials are developed and validated at the Chair for Physics of Energy Conversion and Storage of Prof. Dr. Bandarenka.

Diagnostics

By means of different (in-situ-, operando-) characterization methods, the influence of active material surface treatments, their structural transformations, and their interaction with the electrolyte in an electrochemical cell are analyzed in the group of Prof. Dr. Gasteiger at the Chair of Technical Electrochemistry.

Prof. Dr.-Ing. Jossen's group, Electrical Energy Storage Technology (EES) focuses on rechargeable batteries, with a focus on lithium-ion systems. The research activities include new characterization methods for lithium ion cells and experimental studies on lifetime.

Production

The Institute for Machine Tools and Industrial Management lead by Prof. Dr.-Ing. Reinhart takes the battery materials to the next step - full cell production. In their over 200m^2 sized laboratory, a full cell assembly line is tested for different battery chemistries, from traditional lithium-ion to solid-state batteries.

Integration and application

In the group "electric powertrain" of the Chair of Automotive Technology of Prof. Dr.-Ing. Lienkamp, the challenges of integrating lithium-ion batteries into electric vehicles are tackled. The topics of research are state estimation, fast charging, thermal design and aging – all on cell level, but especially with respect to higher system levels.

The research of Prof. Dr.-Ing. Jossen includes optimization of operating strategies, modeling of single cells and battery systems and development of battery management systems. Many of our research projects target current challenges like the need for e-mobility, charging and for stationary storage of electrical energy from renewable sources.

Putting all this expertise and players together, we expect to create outstanding synergies and the appropriate momentum to initiate new interdisciplinary collaborations and projects between the groups at TUM and with third parties.

Current activities

Further some of the existing collaborations from the researchers community are described:

All Solid State Battery – ASSB Bayern

In close cooperation with industry scientists of different thematic fields (physics, (electro) chemistry, materials science, process engineering, production) work together on the development of solid state battery cells. The project will be realized in several steps. At first step, research activities on material synthesis and characterization of selected material classes are already being carried out. In the medium term, solid electrolyte systems are to be developed, optimized and tested in single-layer pouch cells. The goal is to produce small-sized single-layer cells in the range of 1 to 15 cm^2 and a capacity of ≤ 50mAh towards the end of the second project phase. For this purpose, new material classes of solid electrolytes are being developed and investigated as hybrid polymer systems with proven anode and cathode materials. The ZAE Bayern is involved with its materials science competencies in component manufacturing and characterization. The researchers work closely together with Bavarian industry to transfer developments into industrial cell production. The project is funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy.

e-conversion

e-conversion is a new Cluster of Excellence funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) with a focus on investigating fundamental mechanisms of energy conversion processes. Research thrusts will address e-conversion processes at interfaces between different solid phases, between solids and liquids, and between molecular layers and solids. Unprecedented synergies, cross-fertilization and coherence of the research program arise from materials and processes common to different energy applications, and from different interfaces all contributing towards specific energy functions. [More information: https://www.e-conversion.de/about-e-conversion/]

ExZellTUM – Center of Excellence for Battery Cells at the Technical University of Munich

The ExZellTUM WING center is a collaborative effort ranging from electrode formulation development, over the electrochemical characterization of electrodes and the upscaling to multi-Ah cells, all the way to modelling of performance and cell ageing. Involved are four groups from the Technical University of Munich (TUM), namely the Institute for Machine Tools and Industrial Management (iwb), the Chair of Electrical Energy Storage (EES), the Chair of Technical Electrochemistry (TEC), and the group Advanced Materials at the Neutron Source Heinz Maier-Leibnitz (FRM II). One of the specific objectives over the past six years of the ExZellTUM WING center has been the optimization of large-format pouch cells, incorporating novel cathode materials and water-based graphite anodes.

ZEI battery lab

The ZEI battery lab opened doors in May 2017. Since then, a substantial number of experimental equipment has been installed. As of the end of 2018, the lab equipment includes an experimental pouch cell manufacturing machine, two glove boxes, a high-precision dilatometry cell, three climate chambers and several potentiostats and battery cyclers.

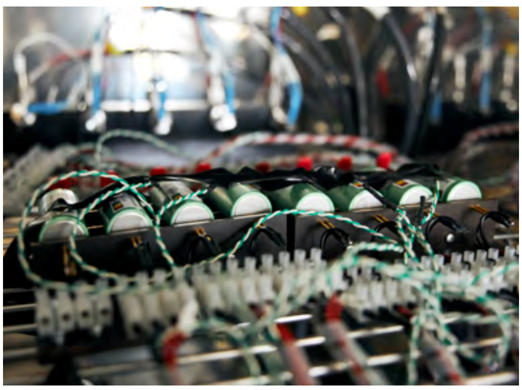
Stefan Hobmaier / TUM

View into the ZEI battery lab with glove boxes for pouch cell manufacturing in the background

Both gloveboxes are filled with dry argon gas, so that the battery materials inside cannot react with oxygen or water. One of the two gloveboxes is used for opening commercial and experimental cells and harvesting the materials found inside the cells. This can be necessary to determine the parameters for a physics-based cell model. Those parameters could be the thickness of each electrode (cathode and anode), the thickness of the separator (the electrically insulating membrane between anode and cathode), the specific weight of each component etc.

Other parameters require elaborate methods: Small laboratory cells are used to test the specific capacity of each electrode, the thickness change of an electrode per charge stored can be measured via an electrochemical precision dilatometer.

Stefan Hobmaier / TUM



The techniques described above have been used in many joint projects with TEC and iwb and have helped to produce relevant scientific output in the field of lithum-ion batteries.
The results from these measurements have contributed to important publications, which are found in the Publications section of this report.

Battery cell test rig.

Center for Power Generation (CPG)

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is coordinating research on new and innovative technologies for electricity generation and storage. Research projects cover many aspects of energy conversion. The Center for Power Generation (CPG) provides an excellent interdisciplinary environment to enable efficient collaboration across departmental borders through the transfer and combination of knowledge and resources from several institutes at the Munich School of Engineering (MSE).

The CPG coordinates research on multiple topics related to energy conversion: geothermal power generation, biomass utilization, control systems, flexible conventional power plants and Power-to-X systems. It links several TUM institutes from different departments and faculties and successfully initiates research projects.

Currently, CPG researchers are involved in many projects, including “Energy Valley Bavaria – Flexible Power Plants”, “Geothermal-Alliance Bavaria” and “Clean Tech Campus”. Besides these central projects, the member institutes do research in many more areas. The CPG serves as a competent contact for interested parties and potential partners – and new members are always welcome!

This report about CPG activities summarizes the motivation for research, identifies key technologies that are covered and gives an overview about some ongoing projects.

Motivation for research

The rapid technological and economic development in many countries, especially in emerging markets, and the increasing world population lead to a continuously growing energy demand and have caused a significant increase in CO_2 emissions of approximately 50% within the last 20 years. On the one hand, considerable efforts are made to increase energy efficiency on the demand side and boost the share of renewable energy sources for power and heat production. On the other hand, utilization of waste or low-temperature heat sources is investigated as another option to reduce overall global greenhouse gas emissions.

In Germany, the generation of electricity accounts for roughly one third of total CO_2 emissions and offers high potential for reduction. However, despite increasing shares of renewable electricity generation, the government’s 2020 reduction targets will be missed. From 1990 to 2018, Germany’s CO_2 emissions were reduced by approx. 30%, but the reduction target of -40% until 2020 will most likely be missed. The German federal government also announced goals for 2030 (-55%) and beyond. Considering these goals, energy markets need to and will change significantly in the coming years.

Most experts assume that the overall consumption of electricity will not significantly decrease in the future, but might even increase if sector coupling (mobility / electricity / heat) is extended. Hence, new and emission-free technologies must be integrated into our existing infrastructure in order to reduce CO_2 emissions. This integration must guarantee a constant, reliable and affordable energy system for consumers and industry and is a long-term effort. This is exemplarily shown by the latest agreement on coal exit strategy until 2038.

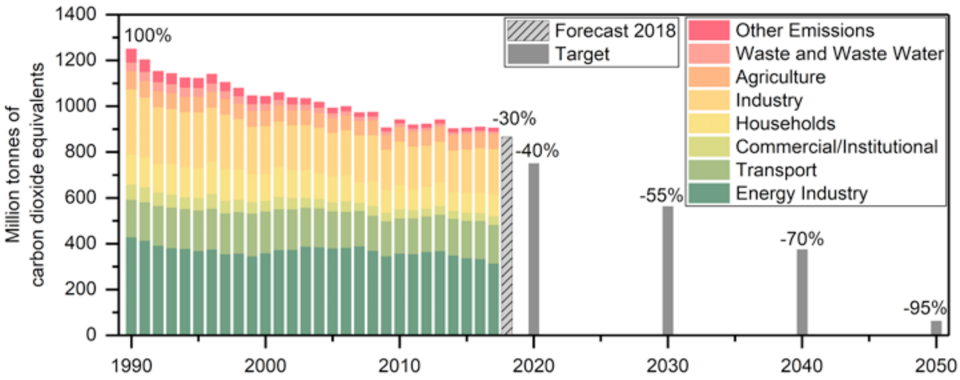

Fig. 1. Emission of greenhouse gases covered by the UN Framework Convention on Climate (1990 – 2018)

Power generation in a changing market

In the past, the German energy system was mainly based on conventional fossil fueled power plants (coal, gas and nuclear). The ongoing transition of this system to increasing shares of renewable sources requires fundamental research in different areas.

Although conventional power generation capacities started to decrease in the last years, they will play a key role to guarantee the security of supply in the future. At the same time, the installed capacity of renewable power generation (mainly wind and solar) is increasing and will be expanded further.

The increased fluctuating power supply from wind and solar sources results in various challenges regarding their integration into the energy system, like short-term balancing, back-up power plants, base-load capability of wind and solar power, and overproduction. In order to balance the intermittent power generation from wind and solar, other renewable sources like geothermal energy or biomass might be used and will become more important in the next few years. Currently, energy storage applications only play a minor role for stabilizing the energy system, and instead focus on maximizing self-consumption in home systems or profiting from price spreads. Nevertheless, studies predict that the storage of electricity will become necessary in large-scale applications after 2035.

Research scope of the CPG

The scope of research covers several areas: power plant technology, renewable energy integration and storage, modeling and simulation. A special focus lies on new technology development, efficiency and flexibility increase, and emission reduction of geothermal, biomass, gas or coal fired power plants with Rankine cycle power generation. Although the fundamental working principles of conventional power plants have been known for well over 100 years, a range of promising optimization measures exists. Due to the increasing importance of matching volatile supply with steady energy demand there is an additional focus on technologies for storage and on enabling of sector coupling.
As electricity from renewable sources will be the basis of our future energy system, the efficient transformation of electricity to other forms of energy, e.g. heat, fuels, chemicals or

its direct use in mobility applications are the most relevant forms of sector coupling. Activities in this field are summarized as Power-to-X and will profit from increasing research efforts in the next years.

Conventional power plant technology

Commonly the term "conventional power plants" refers to electricity generation through Rankine and Joule cycles. Research on this topic is primarily associated with combustion technologies, steam generation at high pressures and temperatures, power plant dynamics and control, design of efficient thermodynamic cycles and optimized steam and gas turbine technologies. At the same time, the efficient utilization of low temperature heat sources (geothermal or industrial waste heat) is investigated.

Electrical power transmission

Reliable grid design and development will become more and more important in the future, especially with further increasing shares of wind and solar power generation and fewer centralized high capacity power plants. New transmission lines are required to transmit large amounts of wind power from northern Germany to industrial centers in the south. At the same time, local and decentralized power generation requires a completely new grid topology.

Flexibility increase and plant control mechanisms

To date, a characteristic feature of most of the existing steam power plants is their design for base load operation. Operational flexibility has often deliberately been limited to 200 cold start cycles throughout the plants lifetime. Driven by an increased share of renewable (and volatile) power generation especially in the German grid, previous base load plants now need the flexibility for frequent load changes as well as cold and warm start-ups. Power plant materials have not been designed for such requirements and hence, especially thermal stress becomes an issue. Therefore, exact knowledge of material properties and material lifetime when exposed to these new operating conditions becomes vital.

Energy storage and power-to-x

Along with flexible power plants and transmission grid improvements, energy storage technologies will gain more importance in the future, when they are needed to balance the fluctuating electricity production of wind and solar power plants. Technologies for short-term storage of heat are already state-of-the-art, but storage options for electricity are not yet commercially available on the required TWh scale. The largest electricity storage plants that do not depend on geological formations currently in construction are a 720 MWh Lithium-Ion battery and an 800 MWh Redox-Flow battery in China are still small in comparison to the necessary storage capacity. As the costs for these technologies are still high, regardless of economies of scale, non-electrochemical energy storage is better suited for many applications. Several different technologies are promising, especially thermo-chemical storage and Power-to-X solutions.

Current activities

The Center for Power Generation is actively involved in several projects and activities within MSE. Besides the main projects outlined in the next paragraphs, the center is working on numerous additional projects. For more information, please visit our website: **https://www.mse.tum.de/center-for-power-generation**.

Energy Valley Bavaria - flexible power plants

The CPG is involved in the Bavarian state-funded project "Energy Valley Bavaria". The sub-project "Flexible Power Plants" is a collaboration of four CPG institutes and focuses on increasing the flexibility of current conventional power plants. The interdisciplinary team is researching innovative technologies, their integration into the power system, and their influence on the power grids. Experimental investigation of steam generation and gas turbine combustion helps to define measures to improve power plant flexibility. Dynamic process simulations show the impact on load behavior and the lifetime of critical components. The future development of the European energy system can be analyzed with the help of system studies and grid simulations.

Geothermal Alliance Bavaria – combined heat and power technology

The project scope calls for research into the optimization of geothermal CHP and ORC technology. At the Chair of Energy Systems, a new ORC-CHP test rig has been constructed that addresses the experimental proof of several measures for efficiency enhancement. Besides the plant architecture itself, the working fluid has significant influence on plant operation and efficiency, which strongly depends on boundary conditions such as heat source temperature or heat demand of district heating. The new test rig is compatible with various new-generation working fluids in order to identify optimal fluids for different boundary conditions. Furthermore, plant operation is optimized by investigating control strategies in practice. The focus is on efficiency enhancement in part load operation and on optimization of dynamic behavior. More information on the GAB can be found in its own section.

CleanTechCampus

Based on the results of the MSE seed funding project 'CleanTechCampus Garching', several members of the CPG successfully acquired funding (1.2 Mio €, 3 years) from the Federal Ministry for Economic Affairs and Energy (BMWi) for a follow-up 'CleanTechCampus' project. The goal of the new project, which started May 2016, is to develop a roadmap for the energy future of the University Campus in Garching, including a detailed analysis as to where and how novel energy saving, cooling, heating or electricity generation and storage technologies can be effectively integrated to locally achieve a more sustainable energy future. The novelty of the project lies in its integrated approach, centered around the simulation tool 'URBS' allowing to simultaneously optimize the heating, cooling, electricity supply and distribution system, and to assess the impact of renovation, storage and demand side management strategies. The simulation tool allows taking into account future developments of commodity and technology costs, optimizing the system for coming changes in the boundary conditions.

LaBreVer

The joint research project ECOFLEX-turbo LaBreVer (load and fuel flexible combustion) with its research activities in the field of the flexibility of turbomachinery is intended to provide a contribution to the successful implementation of the energy transition in Germany. The aim of this project is to develop concepts for extending the operating flexibility of combined cycle power plants through integrated energy storage and to develop a suitable methodology to optimally design these for various market scenarios. The project shall develop a solution concept for the integration of renewable and conventional energy sources and thereby push technological and methodological advances in important topics such as operation optimization, operating flexibility, hydrogen combustion, optimization of existing plants, decentralization, and energy storage.

Energy Storage (TWIST / TcET): In the course of the German energy transition, thermal storage systems gain further importance, as they can increase both the efficiency and the flexibility required for the energy system. In the previous BMWi-funded project “TcET”, a high-temperature heat storage system has been developed at the Chair of Energy Systems (LES), based on the thermochemical couples $CaO/Ca(OH)_2$ and $MgO/Mg(OH)_2$. In order to ensure a good mass and heat transfer, the reaction was implemented using a fluidized bed process. Decisive progress has already been made in the design and technical implementation, and the “TWIST” project is now building on this acquired knowledge.

Power-to-X

Given the ongoing climate change and the finite fossil fuel resources, Power-to-X processes and water electrolysis will become increasingly important in a future sustainable energy system. Using wind and solar electricity the electrochemical splitting of water (water electrolysis) can produce hydrogen, which can be serve directly as fuel for hydrogen fuel cell vehicles, for industrial applications (ammonia synthesis, etc.), or as a renewable energy storage medium. PEM (proton exchange membrane) water electrolysis is an already technologically advanced method for hydrogen production, which is characterized by good partial load capabilities and high power densities.

Nevertheless, hydrogen production by electrolytic processes currently accounts for only about 4% of the worldwide annual hydrogen production, which is a result of the high costs associated with these technologies.
Typically, PEM water electrolyzers use large amounts of noble metals (platinum and iridium) to catalyze the electrochemical reactions. Besides the high cost of these materials, the limited availability of iridium will become a problem when PEM technology reaches the long-term required GW-scale. Consequently, a reduction of the iridium loading is essential to enable the application of PEM electrolyzers for large-scale energy storage.

Within the “Kopernikus P2X” project, the Chair of Technical Electrochemistry (Prof. Hubert Gasteiger) 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 (see fig. 1a), which results in a significantly lower performance. Consequently, new highly structured catalyst materials with low iridium packing densities are developed which enable the fabrication of a thicker, homogeneous catalyst layer and, hence, a good performance even at low iridium loadings. Since a sufficient long-term stability of

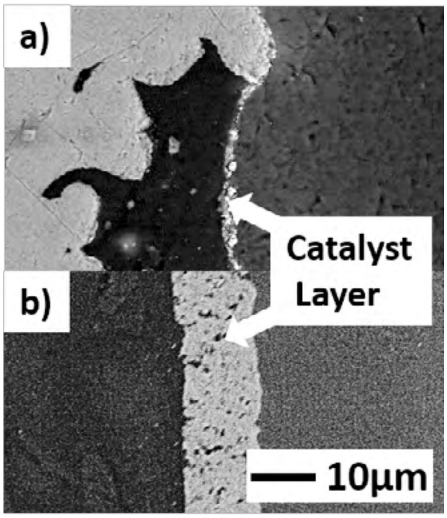

Fig. 1. SEM images of ridium-based anode catalyst layers for a PEM electrolyzer at a total loading of ca. 0.2 $mg_{iridium}/cm^2$:
a) the conventional catalyst produces an insufficiently thick catalyst layer with poor electronic connectivity and poor activity;
b) newly developed catalyst with reduced iridium packing density produces a homogeneous and sufficiently thick catalyst layer with good electronic connectivity and good activity.

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. Within the same project "Kopernikus P2X", 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.

e2Fuels

The project e2Fuels investigates the storage of excess electricity in synthetic fuels. Those fuels are used in the transport sector as well as in stationary applications. The tasks for the Chair of Energy Systems (LES) is to model and optimize the production of those fuels. The entire process from excess electricity to the platform chemicals hydrogen, methane and methanol is thermochemically modeled. To achieve highest efficiencies, the LES focuses on ideal integration of heat and use of by-products. An optimization algorithm optimizes scheduling as well as the size of storages and the size of other plant components. System simulations determine the interaction with the German/European energy system to guarantee synergy effects with the surrounding energy system. In this project, the LES also coordinates the work packages Life Cycle Analysis, OME-Production, studies in the future of PEM-Electrolysis and studies in future sources of CO_2. Overall, this project is carried out in cooperation 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.

BioCORE

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 more efficiently use biogas from fermentation processes in a reversible system. This allows for long-term storage of fluctuating renewable electricity and ultra-high efficiency use of biogas with a single system. The nature of the technologies' double use allows for twice the amount of flexibility that can be offered to the energy system compared to a "producer only" technology. Also, the levelized cost of electricity will decrease compared to non-reversible systems due to higher utilization.

Network for Renewable Energy (NRG)

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is a network for inter-faculty research at the Technical University Munich (TUM) consisting of a multitude of different chairs at TUM, which are interested in the topic of renewable energy. NRG was founded to create the opportunity to promote interdisciplinary, large-scale research projects. The network is focusing 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. With the Network for Renewable Energy (NRG) there exists an interdisciplinary platform to collaborate and spread recent developments within different fields as, e.g. climate-active and therefore sustainable buildings or distributed power grids. Regular meetings within the network foster an active communication between different research groups.

Current activities

From the multitude of activities done by 28 groups from 9 departments of TUM, some examples are selected in the following section. They comprise a scalable method to produce nanostructured electrocatalysts active towards the oxygen reduction reaction, climate and energy active building envelopes, modelling of stationary and dynamic demand behavior considering sectoral and regional characteristics, influence of inertia distribution on local rate-of-change-of-frequency (RoCoF) after power plant outages, stability and interactions of active voltage controllers in distribution grids and superordinate voltage control for low-voltage-distribution grids.

Scalable method to produce nanostructured electrocatalysts active towards the oxygen reduction reaction

Recently, the Bandarenka group developed a simple and scalable top-down technique to produce platinum (Pt)-based electrocatalysts to be applied in polymer electrolyte membrane (PEM) fuel cells. Efficiently catalyzing the oxygen reduction reaction (ORR) is one of the main challenges towards the industrial realization of PEM fuel cell-powered electric engines. Up-to-date, Pt-based nanostructures are still considered as the most promising catalyst materials in PEM fuel cell cathodes, as they exhibit the best catalytic activity for the ORR. Rational design of the catalyst surface is a key step in optimizing the performance of such nanostructures. Particularly, concave surface sites have been found to improve the ORR activity, but synthesis of such structures with wet chemical procedures is typically a complex and multi-step process.

With a simple top-down synthetic procedure, they produced Pt/C electrocatalysts (and alloys, e.g. Pt_xPr/C) with ~2-fold increased activity (~750 mA/mgPt and ~1.3 mA/cm^2Pt at 0.9 VRHE) compared to commercial Pt/C catalysts. By applying a sinusoidal potential to a Pt wire immersed in a KOH solution,

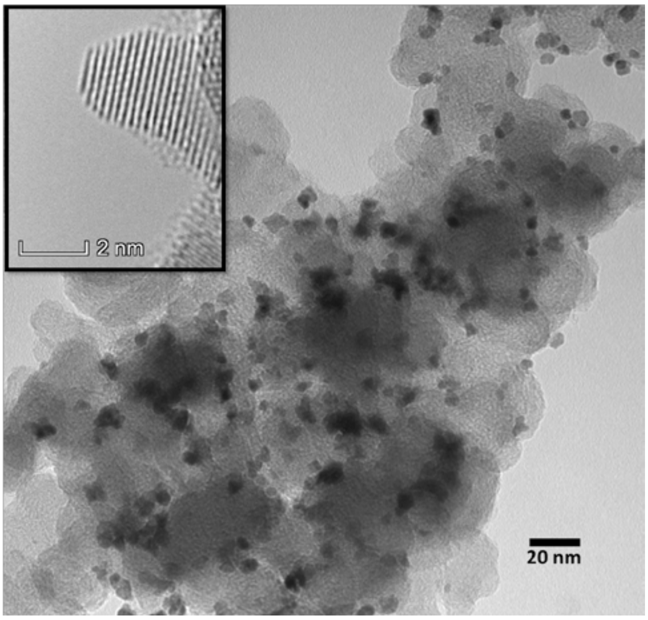

Fig. 1. Transmission electron microscopy image of the Pt nanoparticles supported on activated carbon.
The inset shows the high resolution image of the Pt nanoparticle.

Pt nanoparticles are produced at the surface of the wire, followed by a subsequent release of the particles into the electrolyte. The generated particles have high density of concave sites, as observed in Fig 1. Moreover, accelerated stress tests of the prepared Pt/C at elevated temperatures show improved activity retention compared to commercial Pt/C. In view of the high processing efforts required to produce similarly structured Pt nanoparticles using wet chemical methods, the single step, top-down approach represents a promising alternative.

Cleanvelope: climate and energy active building envelopes

Cities, as key contributors to climate change and at the same time particularly affected by the effects of climate change, are expected to be a moving spirit in climate action, innovative ideas and solutions. The Hemmerle junior research group Cleanvelope investigates how urban building envelopes can be energy 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. The research aims to quantify and potentially improve the impact of a large-scale energy activation of building envelopes on the urban microclimate and outdoor comfort. Another main area of research is the integration of local solar energy solutions into sustainable district and urban energy concepts including the smart use of solar electricity also in the heat and transport sector. Urban district scale energy modelling is used to describe the flexibility and grid-supportive potential. Finally, implementation strategies and development tools for innovative solutions are identified together with cities and municipalities, as urban planning must meet diverse interests and needs of social and economic stakeholders.

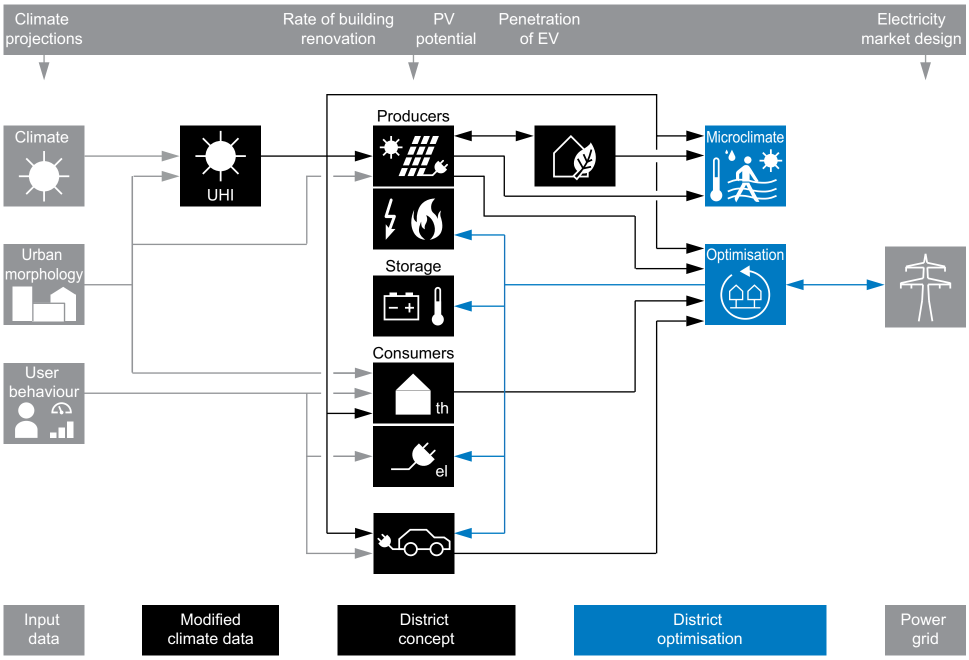

Fig. 2. Cleanvelope model structure

The research group started work in autumn 2018 at the Department of Architecture's Chair of Building Technology and Climate Responsive Design and is sponsored by the Bavarian Climate Research Network (bayklif). First steps included the development of design and assessment concepts for building envelopes with integrated solar energy technologies and building greening. Attractive design studies at district level for selected residential settlement structures accompanied by application guidelines will reduce existing reluctance to apply solar energy systems in building facades. The analysis of synergies and the assessment system will be integrated into urban development tools and thus offer support in taking urban planning decisions. In order to show local and smart use of solar power including marketable interactions with the power grid and to answer urban microclimate questions, a model structure shown in Fig. 2 has been developed. The components include conventional electricity loads, electric vehicle loads, thermal loads, photovoltaic electricity production and any other supply and storage components. To identify optimal schedules for the flexible components a Model Predictive Control strategy is implemented, which takes into account predictions like weather forecasts. The optimization identifies the most cost effective and energy efficient operational strategy, and provides schedules for all flexible components. The graphical algorithm editor Grasshopper will be used as a platform to merge the different components of the analysis: it allows for data extraction from 3D-models and utilizes the returned optimization results for visualization.

Modelling of stationary and dynamic demand behavior considering sectoral and regional characteristics

The transition towards distributed, renewable generation and the subsequent reduced role of large centralized power plants will potentially result in future power systems operating much closer to the stability limits. Consequently, the need for more accurate simulations of distribution systems from the perspective of the transmission grid arises. This is particularly relevant in the case of demand modelling, whereby different types of load exhibit different steady state and dynamic behavior. In order to accurately model demand behavior, the Witzmann group considered a number of factors. Firstly, the composition of demand in distribution systems depends on the geographical region of interest, e.g. areas dominated by heavy industry are characterized by very different loads compared to residential areas. Furthermore, the load composition changes temporally, according to the time of day, day of week, and season. The voltage and frequency behavior of aggregated loads in distribution systems was examined for a range of German regions. Both stationary and dynamic load performance are represented in a single model, considering regional and temporal characteristics (Fig. 3). The results are validated against measured data and the calculated load behavior for a range of German regions is investigated. Finally, the impact of future demand trends (i.e. variable speed drives and LED lighting) on load behavior are examined.

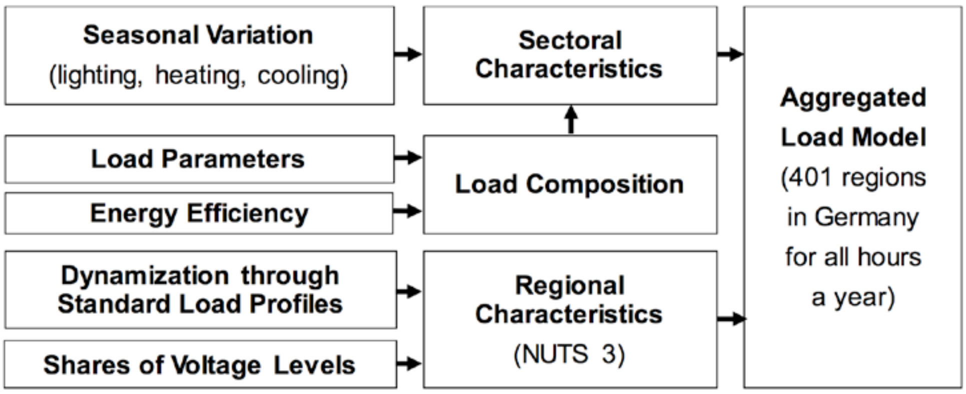

Fig. 3. Illustration of the considered influencing factors in the aggregated load model

Influence of inertia distribution on local rate-of-change-of-frequency (rocof) after power plant outages

The reduced role of synchronous power plants in future power systems caused by the transition towards renewable energy will result in reductions in operating rotational inertia. Under such operating conditions, large power plant outages may cause problematically high Rate-of-Change-of-Frequency (RoCoF), potentially leading to mechanical aging and instability in synchronous power plants amongst other things. In the context of the future Continental Europe transmission system, this topic is investigated by the Witzmann group. Time-series simulations are performed using a detailed electricity market and load flow model of the European transmission system, through which critical hours of low-inertia operation are identified and the impacts of power plant outages are studied. Based on a linearized version of the load flow model, a sensitivity analysis is performed, which provides an estimation of the instantaneous RoCoF that occurs in the regions located close to the outage, as plotted for the modelled years 2015 and 2030 in Fig. 4. The method allows for the propagation of instantaneous RoCoF through the system to be studied. The results are compared to detailed dynamic (RMS) simulations, which indicate that the linearized model approach provides a good indication of the short-term RoCoF behaviour immediately after the outage.

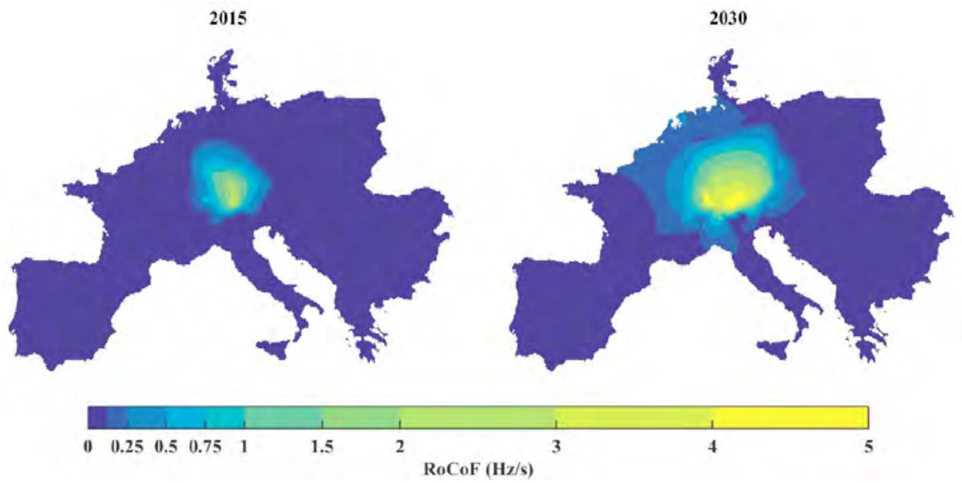

Fig. 4. Modelled RoCoF for 2015 and 2030

Stability and interactions of active voltage controllers in distribution grids

When it comes to the integration of decentralized energy resources (DER) within distribution grids, maintaining acceptable voltage levels becomes one of the main issues. By deploying a clever mix of centralized and decentralized voltage regulating systems, the problem can be solved economically and effectively. The highest efficiency in decentralized voltage control is ensured by the voltage dependent reactive power control Q(V) combined with regulated distribution transformers (RDT). However, due to their feedback-loop character involving the line impedances, stability and interaction issues can arise. These may occur in the form of oscillations or interexchange of reactive power and have considerable dynamic effects on the grid voltage and power quality. To select securely and recommend stable configuration parameters for the Q(V) control as well as for RDTs under varying grid conditions, in-depth inverter, transformer and grid models are being studied by the Witzmann group. To represent accurately real inverters and RDTs, the models are built in EMT (ElectroMagnetic Transients) scale and in dq0-domain and are derived from systematic laboratory measurements. Stability and interaction issues between grid-connected Q(V) controllers is being assessed by means of classic linear control theory in the framework of probabilistic distribution grid structures and future use cases. Possible interactions between non-linear RDTs and multiple quasi-linear inverters with Q(V) are evaluated using the Harmonic Balance method (see Fig. 5a). Therewith, stability limits can be evaluated analytically (see Fig. 5b) and parameter recommendations can be given. The results show that even under realistic worst-case conditions and satisfying given dynamic requirements, the full DER hosting capacity can still be integrated in 99.9 % of all cases. Considering stability of the Q(V) control, there is no practical limitation for the integration of dispersed generation. For the stability limit to be reached, the hosting capacity would have to be increased by 10,000 % at least. The Harmonic Balance analysis between an RDT and multiple Q(V) controllers reveals that a limit cycle and hence a considerable interaction is only possible, if the Q(V) controllers are already in unstable operation without the RDT. It can be shown that, under realistic and reasonable choice of the control parameters, this is impossible to occur and the stability of multiple Q(V) controllers with and without a potential RDT is always given.

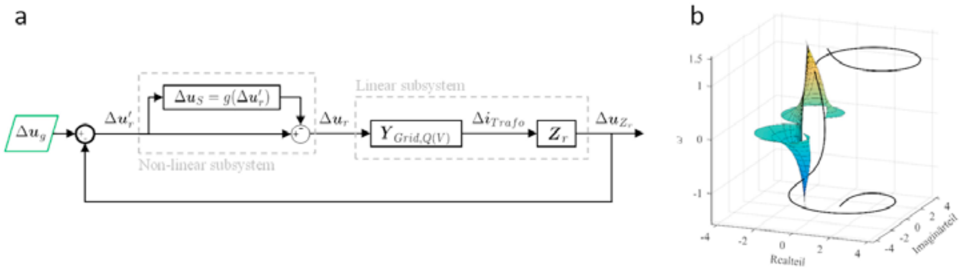

Fig. 5. Equivalent control loop of an RDT (non-linear subsystem) and multiple, grid-connected inverters with Q(V) control (linear subsystem) (a). Exemplary result of the Harmonic Balance method applied on an RDT (colored surface) and an inverter with Q(V) control (black line) (b)

Superordinate voltage control for low-voltage-distribution grids

Future distribution grids will have to be able to provide grid access to prosumers and to fulfill the power quality specifications given in the DIN EN 50160. Both targets should not collide with the principles of a reliable and economical power supply.

Taking advantage of controllable distribution grid utilities (PV-and battery-inverters and line voltage regulators LVR), existing infrastructure could be used to keep power quality within the limits without additional grid extension. The controllable inverters (PV-and battery-inverters and LVR) are provided with standard features for voltage control, e.g. voltage dependent reactive power feed-in. In addition, they could receive reactive power set points transmitted by a superordinate controller, if necessary. The superordinate controller is monitoring all relevant grid parameters gathered by the active utilities. By additionally linking the superordinate controller to the control center of the grid operator, supervisory control and data acquisition (SCADA) capabilities for the low voltage distribution grid is enabled, which allows easy monitoring and manual input. Such a low voltage distribution grid would offer smart-grid functionalities (communication, power quality control, virtual power plant operation).

The results are developed during the government-funded joint research project “Verteilnetz 2020”, including partners from other research institutes (Power Electronics: Institute ELSYS, TH Nürnberg) and industry (distribution grid operator: infra Fürth GmbH; Broad-Band-Powerline: PPC AG; Automation and Telecontrol: IDS GmbH; Batteries: BMZ GmbH / Grass Power Electronics GmbH; PV-Inverters: KACO New Energy GmbH, Line Voltage Regulators: A-Eberle GmbH / Grass Power Electronics GmbH). The project schedule includes simulations, laboratory tests and a field test in the low voltage grid Unterfarrnbach/Fürth.

During this research project in the Witzmann group, a continuously stepping line voltage controller has been developed which is able to supply additional reactive power at its primary side (functionality of UPFC). PV-inverters with improved settling time of reactive power control (~500 ms) and possibility to receive external reactive power set points have been designed. A robust powerline communication against emitted interference from power electronics has been developed. Moreover, different concepts for superordinate control have been investigated.

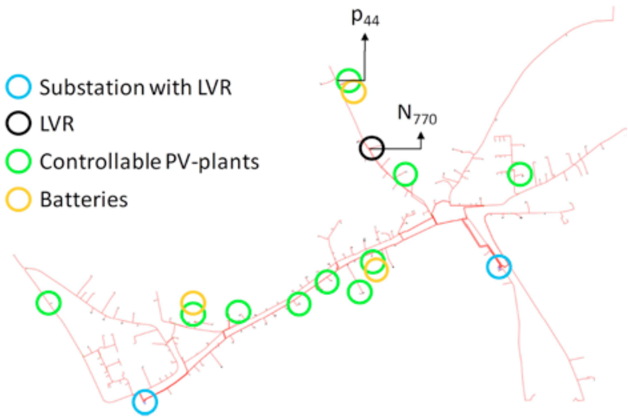

Fig. 6. Field test set-up in Unterfarrnbach/Fürth

In the field test area (see Fig. 6) stepless LVR (2x 630 kVA at the substations / 1x 250 kVA), 10 PV-inverters with functionality of both characteristic curve mode (e.g. Q(V)) and direct set point mode (in total 500 kVA) and 3 batteries (30 kW / 30 kWh each) will be installed. By additionally linking the superordinate controller to the control-center of the grid operator, supervisory control and data acquisition (SCADA) capabilities for the low voltage distribution grid are enabled (this is done using broadband-powerline technology). During summertime at grid node p44 grid voltage up to 250 V can be observed due to an installed PV-capacity of 180 kW_p at the end of the branch (not depicted in Fig. 6).

Energy and Mobility Concepts (EMC)

is working on future mobility concepts, where innovative approaches, such as the DART concept, are disseminated for local use cases in Germany. Mobility today is being disrupted by the so-called three revolutions: electric, shared and autonomous.
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/Busch, Chair of Transportation Systems Engineering/Antoniou) have established complementary expertise in these fields.

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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.

Dynamic vanpool services: Passenger preferences, operations modeling, and simulation-based quantification of impacts (D-Vanpool)

The rapid development of dynamic vanpool services has sparked increased interest in both academia and industry. In this project, funded by DFG in collaboration with the Chinese National Science Foundation (NSF), we investigate fundamental problems associated with dynamic vanpooling from the perspectives of passengers, operators, as well as policy makers. TUM has partnered with Prof. Hai Jiang from Tsinghua University in this research.

Specifically, the objectives of this study are to (i) quantify passengers' preference towards various service attributes of dynamic vanpooling, such as pick-up delay, circuity of the routes, and fare; (ii) build a simulation platform that would allow us to quantitatively evaluate the performance of dynamic vanpooling and its impacts; (iii) develop a high-performance scheduling algorithm, which is a core technology for dynamic vanpooling and should be capable of handling stochasticity in both demand and travel time, and coordinate a fleet of vehicles in megacities like Shanghai; as well as (iv) assess the social and environmental impacts of dynamic vanpooling and identify ways to integrate it with existing travel modes to serve the mobility needs of the residents. The outcome of the proposed project would allow us to gain a thorough understanding of the preferences of the passengers, the operational challenges of dynamic vanpooling, and its impact to building greener and more sustainable cities.

To address enlisted requirements for simulating autonomous dynamic vanpools, we develop several modeling enhancements for the current generation of microscopic traffic simulators. A microscopic traffic simulator combines complex supply and demand models, interacting with each other to simulate a transportation environment in detail.

The ongoing supply enhancements address the requirements of modeling autonomous van behavior and passenger trips. To adequately simulate vanpools, vehicles should exhibit autonomous driving behavior and an infrastructure to support their door to door pick up and drop off service. To model individual passenger trips, separate additional facilities are required to capture individual passenger trip variables. In this research, the considered van capacity is between 8 to 14 passengers.

Fig. 1 outlines the overall architecture for modeling dynamic vanpooling services. The current implementation, developed by TUM, utilizes scheduling algorithms, developed by Tsinghua University, interfacing using python with the microscopic traffic simulator SUMO.

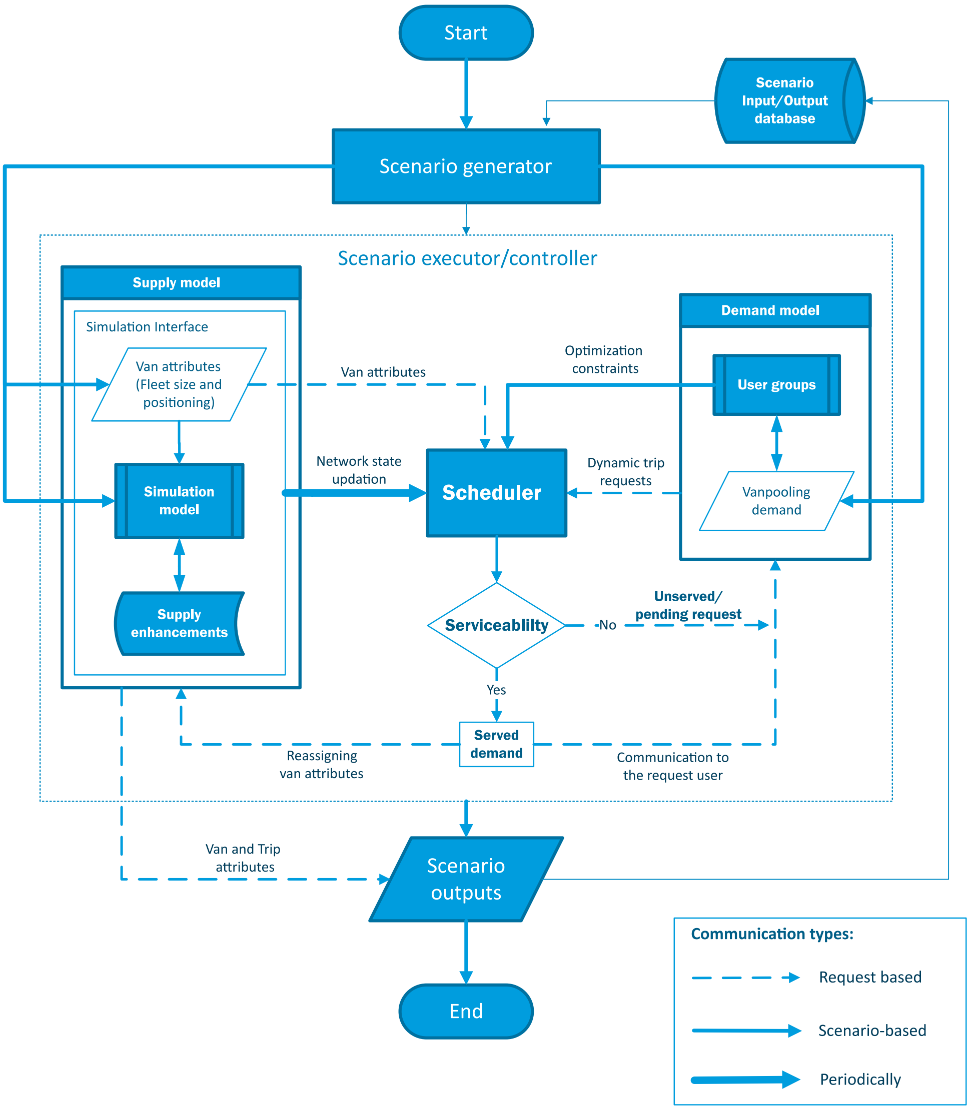


Fig. 1. Generic architecture for modeling dynamic vanpooling services

Wider impacts and scenario evaluation of autonomous and connected transport (WISE-ACT)

This Action, funded within the EU European Cooperation in Science and Technology (COST) framework, aims to consider and quantify the impacts of autonomous vehicle (AV) trials, which are currently taking place worldwide. Europe, and Germany in particular, play a big role in these developments, but, still, very limited research exists on the broader impacts of deployment of such vehicles. Issues such as compatibility with existing infrastructure, and transition of control are largely unknown.

It is expected that the widespread use of AVs may improve network efficiency and road safety, while reduced energy consumption, improved air quality and better use of urban space may also result. This COST Action, in which TUM participates actively, leading Working Group 5 “Scenario Development”, aims to quantify expected future mobility trends and impacts on mobility behaviour. The Action aims to explore these issues in a holistic way, considering also impacts that are often overlooked, such as social, ethical, institutional and business impacts under various deployment scenarios.

The Scenario Development and evaluation work develops a thorough experimental design and utilises both pre-existing and new simulation data to conduct various analyses. The key tasks of this activity are to (source: COST Action CA16222 Memorandum of Understanding):

- “Develop and evaluate a number of scenarios of AVs deployment throughout Europe;
- Compare the results of simulation analyses across different localities; and
- Develop a set of criteria and indicators which can inform policy makers about deployment of ACT in a certain locality.”

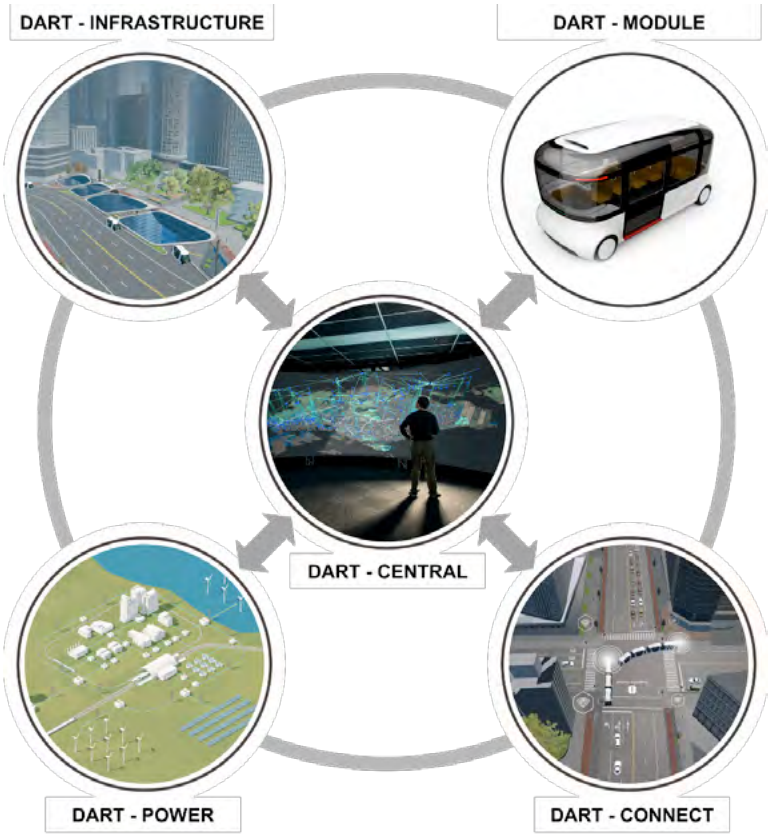
To implement the proposed extensions, existing available simulation facilities have been explored . Since each simulator facility contains its own backend application program interface (API), the possibilities or difficulties for developing the extension platform can actually vary among different simulators. Therefore, an open, simulation-agnostic platform is being developed, which can be extended easily by additional functionality. Two simulators (SUMO and AIMSUN) have already been integrated to the platform, while other Action partners extend the functionality with additional resources. The framework is being tested on the Munich network.

Furthermore, to understand the idea of an overall extension framework, prototype case studies of modeling shared autonomous vehicles (SAVs) have also been built using python, along with dynamic visualizations. This prototype is being further extended, including all required extensions and improving the dynamic graphical representation.

Towards the ultimate public transport – TUMCREATE Singapore (DART)

TUM and the Nanyang Technological University in Singapore co-operate in a large scale interdisciplinary project at TUMCREATE research institute in Singapore. The research initiative “towards the ultimate public transport” is funded by the National Research Foundation of Singapore and includes TUM’s Chairs of Traffic Engineering and Control (Prof. Dr.-Ing. Busch), Renewable and Sustainable Energy Systems (Prof. Dr. Hamacher), Automotive Technology (Prof. Dr.-Ing. Lienkamp), Robotics, Artificial Intelligence and Real Time Systems (Prof. Dr.-Ing. Knoll) and Industrial Design (Prof. Frenkler).

The goal of the project is the holistic design of an autonomous and electrified public transport system that services low demand feeders as well as corridors of higher capacity. The system called DART (Dynamic Autonomous Road Transit) is seamlessly integrated into the urban transit system and its control infrastructure. The multi-disciplinary team of TUM comprises the key competencies to design all of the DART's components (s. Fig. 2).



Source: TUMCREATE

Fig. 2: TUMCREATE; Mid term report of the project „Towards the Ultimate Public Transport System“; Singapore 2018

DART OPERATION is based on autonomous and electric modules that accommodate thirty passengers. The modules can link electronically and form platoons that navigate through the city as road trains. The DART INFRASTRUCTURE consists of intelligent traffic control that ensures a smooth journey with no unnecessary time losses, charging infrastructure for the modules as well as intelligent stops that are optimized alongside the vehicle to ensure fast boarding and alighting. DART POWER optimizes power supply and power management of the vehicles with respect to the boundary conditions of the power grid and the transit operation. DART CONNECT designs the communication mechanisms between the single modules as well as between modules and the infrastructure. Finally, a DART CENTRAL links all the functions of transit operation, traffic control and power supply to ensure a coordinated operation of the transit system.

The main fields of cooperation between the transportation engineers and electrical engineers in this project is the coordinated planning of the transit system layout and the optimizing of demand for public transport services, operational necessities such as necessary stops for merging and splitting module platoons as well as the optimal form and location of charging infrastructure. Additionally, the two disciplines cooperate in the design of the hardware for stopping facilities and pavement that must meet the requirements of travel comfort, durability and integration of charging infrastructure.

Future activities

DART@Landkreis München

Together with the district of Munich, TUM MSE has the ambition to implement the DART concept also in Bavaria – in order to create benefits for the suburbs where new business parks are created at an incredible pace. The connection with track-bound subway or suburban trains in due time turned out to be an impossible task. In order to satisfy transport needs and to support the transition from individual transportation towards more sustainable solutions, the DART concept is able to use existing infrastructure combined with a rapid implementation. Due to its modular nature, it is ideally suitable to serve the last mile, penetrating into the residential areas.

Therefore, initial discussions took place in 2018 together with the district administration and several stake holders. The TUM vision incorporates a three step program, where the campus in Garching is accessed by autonomous busses from the central metro-station. The campus is the ideal test bed due to moderate interactions with urban road systems. The second step will connect the neighboring community Dietersheim to the campus and the metro station. The final step for demonstration will be the connection to the airport and the adjacent communities.

Current bus connection is rather scarce; one bus during off-peak and two busses during peak hours. Also connections to the airport take 45 mins of travel time and at least one change of transportation system. The benefit for the communities, the region and last but not least for TUM will be huge.

Currently TUM MSE and the district administration of Munich are looking for public funding in order to realize the first stage of the demonstration. Suitable industrial partners are at hand. Together with accompanying research projects, the whole implementation phase will be analyzed and evaluated.

Center for Sustainable Building (CSB)

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("Zentrum für nachhaltiges Bauen", ZNB) unites competences of TUM in the field of sustainable design and building, especially from the faculties of Architecture, Civil, Geo and Environmental Engineering and the Department of Electrical Engineering and Information Technology. The participating institutes are Building Physics (Prof. Dr.-Ing. Klaus Peter Sedlbauer), Energy Efficient and Sustainable Design and Building (Prof. Dr.-Ing. Werner Lang), Renewable and Sustainable Energy Systems (Prof. Dr. Thomas Hamacher) and Build- ing Technology and Climate Responsive Design (Prof. Thomas Auer). Beyond the ac- cumulation of competencies, the Center provides the basis for comprehensive scientific exchange between and within TUM faculties and departmental chairs. Also international exchange is fostered and supported as well.

The Center's activities range from fundamental research to practical application. The coordination of the Center is with the Institute of Energy Efficient and Sustainable Design and Building.

Motivation for research

The field of research of the Center for Sustainable Building (CSB) comprises important fundamental topics of sustainable urban and building design and related energy and material flows.

In terms of urban design, the following parameters are examined: settlement density and structure, separation and mixture of functions as well as infrastructure concepts. The use of green technologies are investigated, such as controlling elements for comfort and urban quality as well as other sustainability aspects, since they are of crucial importance for the livability of our built environment.

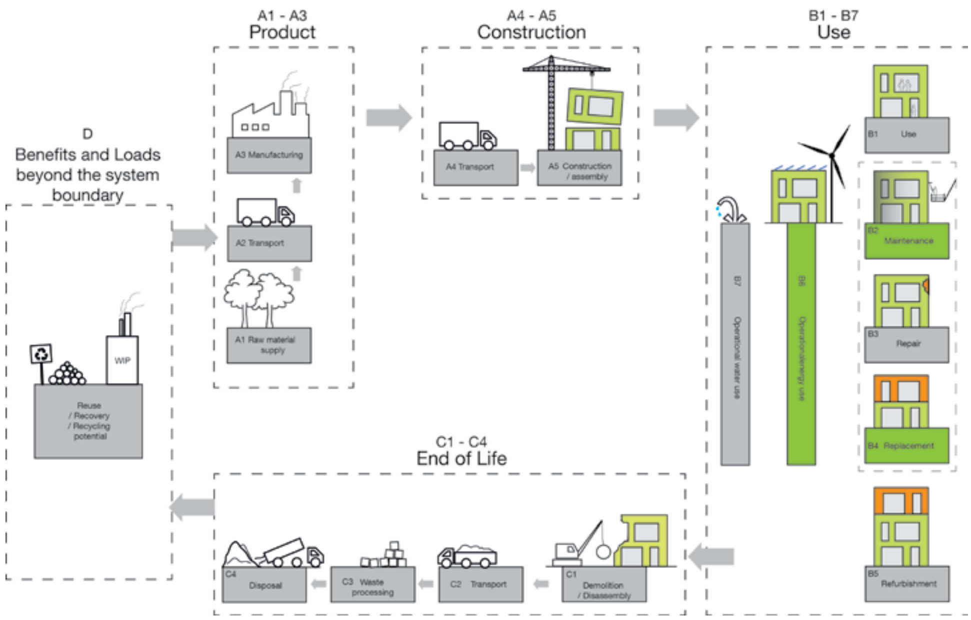
The consideration of local conditions such as climate, topography, geology, infrastructure and the use of renewable energy sources and materials are of priority in the analyses. This is complemented by the integration of function, construction, ecology and aesthetics.

The relationship and interdependencies between function, technology and resource- efficient building activities is a prerequisite. The current state-of-the-art and innovative technologies in solar technology is crucial. The modelling of energy and material flows is of great importance with respect to sustainability. Concepts and strategies are at the foreground, which then lead to adequate use of technology for the architecture, the city and the landscape.

Sustainability in buildings and the construction sector

On an interactive platform, the Balance Laboratory provides specific examples to convey the art of life cycle thinking and to portray the spectrum of its potential applications.

The depletion of resources and the desire to maintain the basis for the development for future generations stipulate a conscious approach with regard to emissions and the consumption of materials and energy. This poses serious challenges to building planners and product designers, since not only the operation or use of buildings and products, but also their manufacturing (construction), recycling or disposal can have significant influence on the total environmental balance. Tackling this complex task requires a high degree of cross-linked thinking and interdisciplinary knowledge in various subject areas. This is why the life cycle and sustainability lab was created under the umbrella of MSE.



■ **Fig. 1: The Balance Laboratory – framework; the different phases of a building lifecycle**

After the development of design, layout and teaching concepts, the backbone of the platform was created, the operating system customized and other technological preparations implemented. Thus the platform was launched and introduced in several courses currently running. Further content extension and platform updates are currently under development.

Numerous research projects underline the importance of this research in the context of a modern society:

Tausendpfund Life Cycle Assessment & Monitoring

The Institute of Energy Efficient and Sustainable Design and Building investigates a holistic approach and technique of monitoring and life-cycle assessment for an innovative and sustainable three-storey office building with a gross floor space of approximately 1,200 m^2. The primary goals are to improve the ecological and economic conditions, the conservation of value, the quality and the comfort of the building.

Design2Eco: Life Cycle Analysis in planning processes of office and administration buildings – decision criteria and optimization possibilities in early planning phases

Design2Eco aims at developing a simple methodology for simultaneous assessment of the environmental impact and costs throughout a building's life cycle, based on the example of office buildings, in order to assist a construction project's stakeholders in decision-making at the early design stages. This methodology is being developed based on the experience gained in research projects carried out at the Institute of Energy Efficient and Sustainable Design and Building (ENPB) together with projects recently completed by the ATP company. **https://www.bgu.tum.de/en/enpb/research/design2eco/**

Eco+Office AS Bau – Life-cycle based CO_2-neutral plus energy building – modernisation vs. new construction of an office building

On the example of the administration building of AS Bau Hof GmbH, the primary energy demand during the whole life cycle should be investigated and optimised. Thereby, not only is the optimization of the building's operating power and its renewable supply repectively, as well as a coordinated load management taken into account,, but also the efficiency increase in the making and disposing of the building (reduction of the part of grey energy). **https://www.bgu.tum.de/en/enpb/research/eco-office-as-bau/**

Current activities

The Center for Sustainable Building is actively involved in several research projects and activities within MSE. The project were highly divers, ranging from new façade solutions to district energy supply solutions. Beyond this, the CSB did support the development of building renovation plans for 100 municipalities in six European countries (i.e. Bulgaria, Croatia, Germany, Romania, Serbia, Slovenia).The next paragraphs focus on selected projects, carried out within the research center.

EmBuild project

EmBuild was a coordination and support project implemented in 2016 by a consortium of ten institutions based in eight countries throughout Europe under the Horizon 2020 Framework Program for Research and Innovation. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) was responsible for the overall coordination. The project was established to empower public authorities at local and regional level to establish a long-term strategy for mobilizing investment in the energy efficient renovation of the public building stock, based on national strategies.

EmBuild primary supported public authorities in Southeast European countries to prepare a long-term strategy for mobilising investment in the energy efficient renovation of the building stock mainly in the following partner countries: Germany, Bulgaria, Croatia, Romania, Serbia, Macedonia, Belgium and Slovenia.

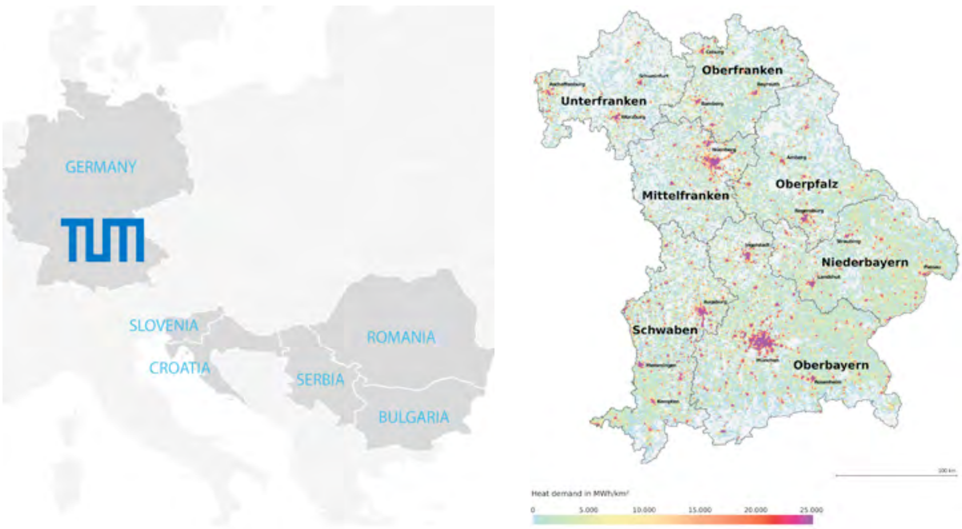


Fig. 2: The impact of Embuild: partner countries and regions

The main objectives of EmBuild were to increase the capacity of public authorities at regional/municipal level to collect the necessary data to prepare ambitious, sustainable and realistic renovation strategies for public buildings, analyse and identify cost-effective approaches to renovations, guide investment decisions and facilitate private sector involvement. In addition, the project will focus on analysing policies and implemented measures that stimulate cost-effective deep renovation of buildings and identify best practices in six partner countries.

The Center for Sustainable Building thereby focused on the analysis, quantification and communication of the so-called wider benefit - the impacts of energy efficiency and deep renovation - which go beyond energy savings. Most energy efficiency-related improvements trigger gains in economic, social and environmental sectors. Most benefits, like job creation, have an impact on the whole economy of a municipality, a region or even a nation. This socio-economic analysis was integrated into the policy and decision-making circles in several municipalities in the project's partner countries.

Project achievements:

- Building renovation plans following the EmBuild concept adopted for more than 100 municipalities in six countries (Bulgaria, Croatia, Germany, Romania, Serbia, Slovenia).
- Implementation of these plans will result in total savings of 328 GWh/ year.
- More than 40,000 public officials in Europe benefitted from the project, and at least 1,500 of them were directly involved, e.g. during trainings, workshops and roundtable discussions.
- Project-related information and results are available for further reading and for free download from the EmBuild Navigator

EmBuild added a new, profound layer on the research activities of the CBS. Focused on policy making, urban planning and a direct collaboration with implementing partners like cities. A project related to this approach but established at the CBS member: Institute of Energy Efficient and Sustainable Design and Building, is described in the following paragarahph:

Green City of the Future – climate change-resilient neighbourhoods in a growing city

The project aims to draw up and develop potential integrated solutions to climate change adaptation, climate protection and infill development in cities, and to test how they can be implemented in planning. To this end, field test sites are to be selected in the City of Munich. This city takes on a specific model character given its growth and its high level of urban density, with its highly-diverse neighbourhood structures and highly-dynamic development. Methods for the development of a multifunctional, networked green infrastructure within dense urban structures will be developed during the project. Simulations are to document the effectiveness of a green infrastructure for the micro-climate and the indoor climate, as well as the urban water budget; the extent to which this information can be put to use in decision-making in planning processes will then be studied in field tests.

The results of qualitative tests on how the population handles heat stress and the potential impact of infill development will complement the quantitative results of the climate simulations.

Research questions

- Which factors and instruments are used for the implementation of planning processes for green infrastructure?
- Which regulatory functions does green infrastructure provide for climate adaption and climate protection?
- How can area requirements for green infrastructure and the demand for residential space be integrated from the perspective of different stakeholders?
- Which obstacles could affect the implementation of green infrastructure measures and how could these obstacles be reduced?

https://www.landschaftsentwicklung.wzw.tum.de/en/research/green-city-of-the-future/

EU-project FLUIDGLASS

The FLUIDGLASS project (2013-2018) was a collaborative project with several partners on EU-level. The objective of the project was to develop a new concept for multifunctional solar thermal glass façade systems, leading to two demonstration containers with a fluid glass façade: One in Vaduz, Liechtenstein and another one in Nicosia, Cyprus. The fluid glass approach turns passive glass façades into active transparent solar collectors which simultaneously control the energy flow through the building envelope. The thermal energy absorbed can be transferred to other parts of the building or, at district level, used within an energy network or collected in a seasonal storage system. Fluid glass increases the thermal performance of the whole building resulting in energy savings, while at the same time significantly improving the comfort for the user.

Fluid glass unites four key functions in one integrated system:

- Transparent solar thermal collector,
- Transparent insulation layer,
- Overheating protection system and
- Heating and cooling device.

Lang / TUM

Fig. 3: the colouring of the fluid glass prototype

In the project, the CSB focused on thermal and daylight simulations in different scales and on Life Cycle Analyses (LCA). The simulation results at the locations Moscow, Munich and Riyadh - using the simulation models developed by the CSB – proved the hypotheses that office buildings fully glazed with fluid glass are energy efficient and at the same time allow for a very high thermal and visual comfort.

Increase of the urban use of renewable energies through low temperature district heating networks

The project investigates the energy efficiency potentials of Low Temperature District Heating Networks through the utilization of volatile and waste heat sources. The advantages of such networks are:

- absorption of renewable low-grade heat,
- reduction of thermal losses and
- optimization of the overall energy efficiency of the system through the temporal and spacial shift of heat within the district.

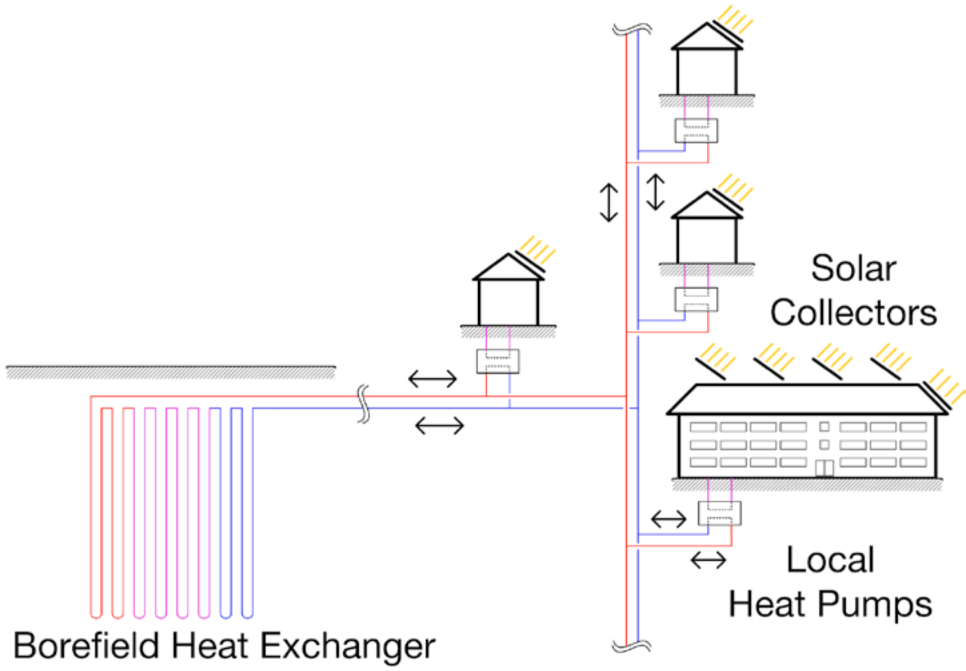


Fig. 4. Model grid for low temperature district heating networks. Source: Heißler 2018

A prerequisite for the utilization of these benefits is a fundamental understanding of the limits of this technology, the framework conditions of use, the economic efficiency and the operational interdependences during the use of the network. On the basis of an exemplary district with high urban density, the research project analyses: heat demand limits, storage capacity and seasonal use of network and storage, as well as the profitability of the low-temperature district heating networks.

The investigations show that low temperature district heating networks are able to fully supply districts of EnEV (Ger: Energie- Einsparverordnung, German Energy efficiency directive) New Construction buildings or of higher standards in middle-Euopean latitudes with solar thermal heat. Under these conditions up to 85 % of thermal losses and 65 % of CO_2 emissions, compared to a traditional district heating network at identical load conditions, can be avoided. However, the implementation of such systems is prevented or heavily impeded by the current legal situation put into effect to regulate the traditional producer-consumer structure. Neither is it stipulating an energy exchange between buildings within a district nor a change of part of the market players from consumer to producer or vice versa.

This research project was funded by the research initiative “Future of Building” (“Zukunft Bau”) of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) (SWD-10.08.18.7-15.33).

Center for Combined Smart Energy Systems (CoSES)

is a central platform for joint research on smart renewable energy systems. The integrated approach is reflected by the cooperation of different institutes. The Director of the Munich School of Engineering, Prof. T. Hamacher, is also responsible for CoSES. Alongside him CoSES is jointly directed by the heads of the participating institutes, Prof. R. Witzmann, Prof. U. Wagner, Prof. W. Kellerer, Prof. S. Hirche, Prof. T. Hamacher, Prof. W. Utschick, Prof. H.G. Herzog and Prof. C. Hackl. Directing decisions are made by a consensus among them.

The scientific objectives of the center are to better integrate 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. Energy demands include heating, cooling and electricity demand also induced by electric mobility.. The interaction between systems and buildings, their communication and control is investigated applying state of the art means of digitalization

The entire center is organized by five subprojects (SP), according to the specialization of the individual partners.

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Motivation for research

Environmental consequences like the greenhouse effect, burdens from the use of fossil fuels, have led to a change in public attitudes. The desire for clean and sustainable energy and the technological advance have initiated the success of renewable energy sources (RES). This ongoing change within the energy supply leads to a change within the supply conditions. While in the past, large power plants were responsible for most of the energy supply and system control, new approaches are necessary in order to integrate a large proportion of RES and to maintain a stable system. Possible concepts for these challenges are smart grids and synergies among different sectors, which lead to interdisciplinary research in simulations and experiments.

The CoSES laboratory

CoSES microgrid laboratory comprises building emulators which are connected by three grids – communication, heat and electricity. The Hardware-in-the-loop (HIL) philosophy is at the core of the design of electrical grid and heating grid, and is interconnected in real-time by the communication grid. The real world analogy of the lab is a microgrid of five buildings: four single-family houses (SFH) and one multi-family building (MFH). The interconnections form an electrical grid and a heating network, allowing for sector coupling, robust pricing mechanisms and having a decentralized grid control with high shares of RES.

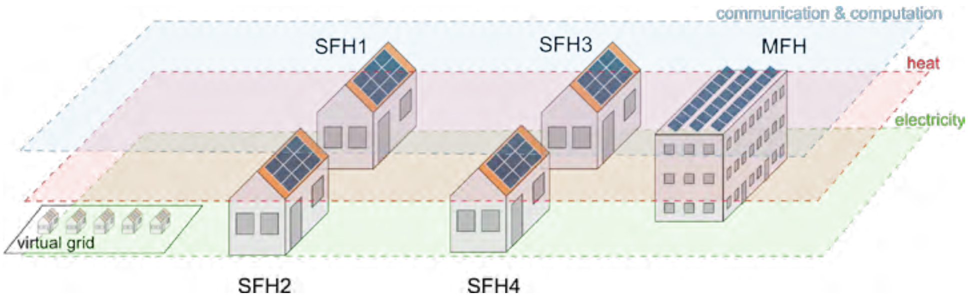

Fig. 1. Three layered grid schematic for CoSES

CoSES electrical grid

The electrical grid in CoSES allows a variable grid topology. It can be converted from a radial to a ring configuration. Here the five houses mimic a real world decentral housing colony in their electrical capacity, available technologies and the cable distances between them. A set of power cables, approximately 1.4 km in accumulated length, is buried in the foundations of the ZEI building. A patch panel allows to change the configuration and length of cable between the seven grid nodes. During normal operations, CoSES electrical network is connected to the public electricity grid through two 250 kVA transformers. Tap changing transformers provide some measure of control over the distribution grid voltage, which gets affected by high penetration of PV at household level. The PV modules on the rooftop of the ZEI building can be connected to the building emulators as well as central and decentral battery storages, electric car chargers and synchronous generators. A variety of precise current and voltage transducers at all grid nodes of this network, sampling at up to 10 KHz, provide measurements for closed loop control and power management operations.

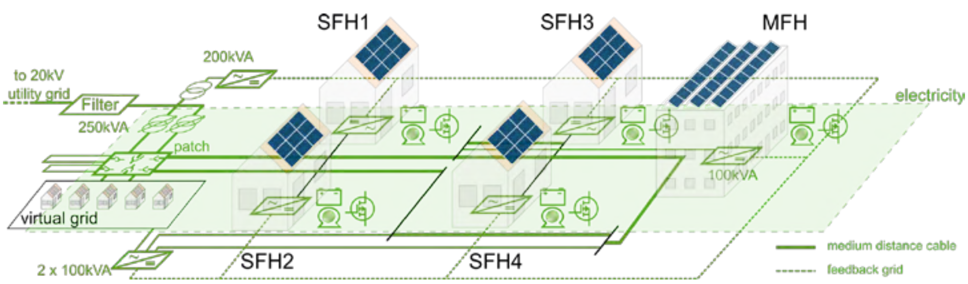

Fig. 2. CoSES electrical grid schematic

Residential electrical demand has evolved due to addition of big flexible loads such as car chargers and prosumer (producer & consumer) capabilities from roof top PV systems. CoSES uses seven bi-directional converters 150 kVA each to emulate electrical demand with prosumer characteristics. The parallel converter lines are connected to the five houses emulated in the lab and two extra lines can be used to emulate a grid extension model. The prosumers are fully controllable, thus allowing for dynamic load models instead of averaged out standard load curves and can operate in unsymmetrical configurations. The latter part is an important concept for microgrid operations since the reduced energy pool does not generally provide a guarantee for symmetrical phase balancing of loads. A separate feedback transformer is used to provide an electrical path for the prosumer emulators back to the public grid. The combination of tap changing transformers, buried power cable, bi-directional converter and feedback transformer ensures that, while no energy is wasted except line losses in this loop, up to 200 KVA of prosumers can be emulated and all currents and voltages, with their associated harmonics, are measured at their distribution grid levels.

The active components in the electrical grid – PV inverters, battery inverters, car charging stations, synchronous generators, prosumer emulators and tap changes at the transformer - are controlled by the CoSES control and communication network through digital outputs or PWM signals. There is also an option of using experimentally prototyped PV/battery inverters instead of commercial ones. With high harmonics in the grid and unsymmetrical loading, better regulation is possible using inverter topologies, which have not yet had a commercial breakthrough. Separate FPGA modules are provided at the electrical grid controller, which can be used to run an embedded controller for such inverters.

CoSES thermal grid

Similar to the electrical grid, the thermal grid connects five houses to emulate a small quarter. The thermal grid comprises three pipes for different temperature levels. This enables different grid scenarios such as a standard district heating grid with two pipes, or a district heating and cooling grid using two or three different temperature levels. Each house has a bidirectional heat transfer station, allowing prosumer behavior for thermal power. Prosumers can export excess heat to the grid or import required heat from the grid. Also heat transfer stations with heat pumps can be integrated, allowing the use of low temperature district heating grids to minimize energy losses. Those new forms of heat transfer stations require a dynamically operated thermal grid. To mimic this dynamic behavior, a grid emulator is integrated into each pipe in order to reproduce those dynamics for variable distances and variable losses between the houses.

Each house consists of its own heat generator(s), a thermal storage and a heat consuming unit. The individual heat generators vary in size and type; there are combined heat and power units, gas boilers, heat pumps, immersion heaters and emulators for solar thermal panels.

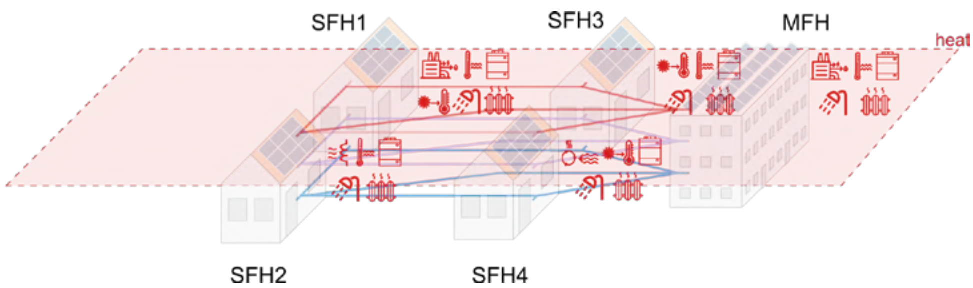

Fig. 3. CoSES thermal grid schematic

The household consumers are emulated by using HiL. Flowrate and temperature of the supply pipe are measured and transmitted to a simulation model of the building. On basis of building parameters as size, age, insulation standard, location and patterns for user behavior or outside weather the simulation model calculates the return temperature, which is then forwarded to the testbed. In comparison to using static reference profiles, this approach allows considering dynamics within the system and thereby representing a more realistic consumer behavior. This is also important in order to evaluate energy management systems.

The heat generators, storage units, consumers and other elements are based on a modular design. This reduces the effort to investigate different setups or to integrate further components, enabling a wide variety of research ideas.

Similar to the electric grid, active components in the thermal testbed – heat generators, control and mixing valves and pumps, are controlled by the CoSES control and communication network. By using precise measurement equipment (e.g. magnetic flow meters and four wire resistance temperature sensors), thermal flows and component operation can be analyzed accurately.

CoSES communication and control grid

The communication and control network in CoSES is based on decentralized real-time targets with shared memory. A simple PC running a general-purpose operating system would not provide accurate matching of processor time and time elapsed in the real world. A real time operating system ensures that a piece of code is solved at and within a specific time. This is important when the result of the simulation involves physical hardware and is thus dependent on the time it takes to finish one calculation cycle. Since CoSES interacts with real world hardware in both electrical and heating grids, it is essential that the operation is deterministic and thus must use real time controllers. The shared memory philosophy is essential to provide consensus solutions to optimal power flow or energy market scenarios. Each prosumer or the grid operator can optimize their operations and maximize the efficiency potential, if they have information readily available regarding production and consumption of energy by every user in the grid. Thus, CoSES communication network creates a collection of all the input and output signal from all the controllers and makes them available to every single real time target in the network. This is achieved by an optic fiber ring link using Reflective Memory technology, which makes all the signals, regardless of their location, available throughout the CoSES communication network. This link updates within 1 ms for all electrical grid signals and within 10 ms for all heat grid signals being measured or calculated.

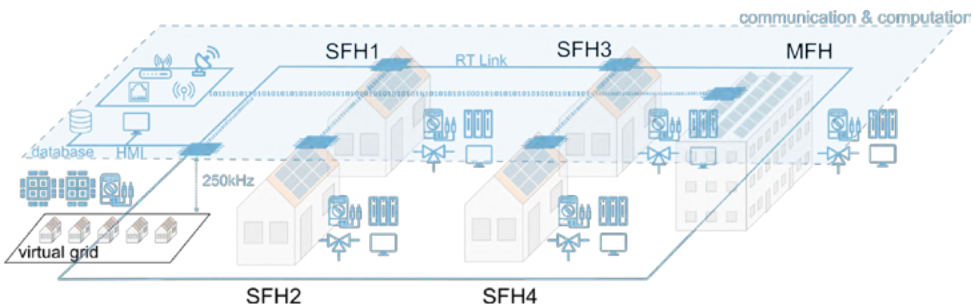

Fig. 4. CoSES communication and control grid schematic

Each of the five houses is provided with a real-time controller setup for the electrical and heat systems associated with that location. Two separate controllers are used to govern the electrical distribution grid and domestic heating grid. The controller setup for each house uses a layered approach to combine the electrical and heat data acquisition system, actuator signals and separate processors. The electrical distribution grid controller collects the current and voltage measurements at the 230 V bus bars to which the houses and the LV side of the tap changing transformers are connected. The heat grid controller works on the domestic heating network emulator modules.

Among other main components, a switch running on IEEE Precise Time Protocol (PTP) 1588 synchronizes the timing of the real time network and multiple host PCs are used to communicate with the controllers. CoSES communication and control network uses a central communication switch board to establish links throughout the lab. This unit can also be linked to cloud-based, wireless, wide area and local area network based controllers. Energy management and sector coupling operations can be influenced by weather phenomena. CoSES employs an own weather station to measure the local global horizontal, direct and diffused radiation, wind speed and ambient temperature.

Stefan Hobmaier / TUM

Due to the integrative nature of the CoSES research center, a variety of software toolchains will be used for specific use cases. The CoSES communication and control grid can integrate almost all such toolchains since it directly uses Dynamic Link Libraries (.dll) and does not rely on any other compatibility checks to let heterogeneous models run together, independent of software platform. This allows the researcher to work within his/her preferred coding environment and not having to learn a new toolchain for every other application. This also allows models and control strategies coded in different toolchains, previously incompatible for co-simulation, to be combined seamlessly and thus expand the scope of the experiment. An example be found in a sector coupling experiment where the electrical and heat load models are developed in separate software and added as modules to the overall CoSES control system in form of .dll files.

Research potential

Covering energy demand only from renewable resources, electrification of the traffic and heat sector, heating networks and new energy pricing structures to incentivize prosumers are three key components of our energy transition aim. However, the gradual migration from a conventional grid to a smart grid brings uncertainties and mismatches between supply and demand, which used to be fairly regulated. One possible solution is to use batteries and heat storages in their respective grids, but further coupling between electricity, heat and transportation must be explored to run the system at its maximum efficiency. These sector coupling ideas are mostly examined with simulated models and approximations due to lack of true data, which does not answer the question – How a smart microgrid in real life could run robustly and reliably using sector coupling for added flexibility?

CoSES provides this unique infrastructure to go as close as possible within the research domain to a field validation for answering the above stated question. By the combination of the three layered grids – electrical, heat and control – within CoSES, a full stack version of a smart microgrid control system which has elements of energy pricing optimization, operational flexibility through sector coupling, voltage and frequency control, harmonic mitigation and forecasting algorithms, can be developed and validated in real time. The combination of the different layers is designed for research issues addressing sector coupling, such as the intelligent control of producers and storage systems or demand side management. Different operation strategies, such as centralized or decentralized operation can be assessed regarding robustness, potential and effort.

Apart from this overarching objective, the individual grids as test benches can answer industry specific research questions. CoSES electrical grid can focus e.g. on voltage control due to high renewable penetration, blackstart of microgrids and harmonic injections at households to reduce voltage distortions at point of common coupling. CoSES heat grid can investigate new approaches for district heating and cooling grids, the integration of prosumers or decentralized heat plants or the use of low exergy energy. CoSES

Stefan Hobmaier / TUM

communication and control grid can be used to test unified protocols for energy management systems, explore secure data handling between prosumers and grid operators and develop innovative communication strategies for specific smart grid components yet still exist within the same control eco-system.

The laboratory is currently in its last steps of putting into operation with the official opening about to come on July 12, 2019. Once in operation, the laboratory will run experiment by relevant end users from research and industry, such as green-tech companies, grid operator for testing new operation strategies or product developers to run realistic tests under laboratory conditions.

Research

Research

Doctoral Program at MSE

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MSE offers a wide range of opportunities for doctorates 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 doctorate 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 schools, the last one dealing with the nexus between food and energy. The doctoral candidates should present their research progress on the MSE-Kolloquium. Since the first candidates started their doctoral program at MSE in 2013, the first doctoral candidates have successfully accomplished their studies in the period 2017-2018.

C. Hamacher / TUM

Participants of the Winter School "Food and Energy" of the MSE Graduate Center

Doctorates in cooperation with universities of applied sciences

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, we cooperate with six Bavarian UoAS:

- 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 at the Graduate School and the MSE Graduate Center, thus becoming cooperative 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, which takes place in November. In addition, the doctoral candidates are offered the opportunity to become a member of a BayWiss-Verbundkolleg.

The International Center for Energy Research

TUM has established strong roots in Singapore by virtue of TUM Asia Pte. Ltd. (teaching) and TUMCREATE (research). Over the last decade, the Nanyang Technological University (NTU) and TUM have become trustful partners in a number of joint research and teaching activities. Beyond that, both universities rank highly by international comparison sharing the advantage of a broad, technically oriented portfolio in engineering, natural and life sciences as well as in management.

Along these lines, NTU and TUM have been collaborating comprehensively to cover the entire field of energy research in the International Center for Energy Research (ICER), established jointly by NTU and TUM.

For this, NTU and TUM agreed about a joint seed funding to finance ten PhD-projects at each university, one PhD student from TUM and one from NTU working together in the same field doing compensatory research in the field of energy. Research in ICER encompasses several aspects of energy-related topics spanning from energy systems to materials with the aim to offer real-world engineering solutions as well as fundamental knowledge advancement. Environmental sustainability, energy efficiency and emissions reduction are the main drivers of the R&D plan at ICER.

The ICER project has been coordinated by Professors Thomas Hamacher at the Munich School of Engineering (TUM), Maria-Elisabeth Michel-Beyerle (CEO at TUMCREATE) and Subodh Mhaisalkar at the Energy Research Institute (NTU). This project was started in 2015 for three years. At the moment, a second phase of ICER is under discussion.

Internationalization

A sustainable energy solution needs a worldwide perspective. In order to find appropriate answers for the future, it is necessary to collaborate on an international level with researcher all around the globe to develop integrated solutions. An appropriate momentum has to be generated towards policy makers and decision makers. As it has been highlighted in the preface: Climate change and resource scarcity are all related to energy and our standard of living.

This section focuses on internationalization in the research context, where the joint research projects together with the National Technological University (NTU) in Singapore are a flagship. Fundamental and applied research questions have been addressed in a collaborative manner on the highest level and quality. Details on this collaboration are found elsewhere in this annual report. However, the research project incorporated a mandatory bilateral research stay of up to six months. Therefore, the ten Ph.D. students from TUM visitid Singapore for longer periods.

Beyond this, scientific exchange has been fostered and supported via bilateral meetings, joint project proposals and the participation in workshops. These activities covered, amongst others, the EuroTech University Alliance members as well as the GlobalTech co-member Imperial College London (ICL). New connections have also been established with the University of Exceter (UoE, UK), École Polytechnique (L'X, France) and Royal Institute of Technology (KTH, Sweden), to name only some of them.

Together with the Gender and Equality Officer of TUM, MSE also tries to expand its diversity and internationalization efforts in order to encourage and support women in their engineering careers. Therefore, MSE is actively supporting applications of post-graduate researchers from all over the world for scholarships and integrates them into ongoing research projects, such as the CoSES[1] research lab, which will be completed in 2019.

Another main pillar to support diversity within TUM across faculties and research disciplines is the annual MSE Colloquium, an exchange platform for TUM researchers. This colloquium has expanded throughout the years and in 2018 it has been able to bring more than 180 participants together.

MSE actively supports the TUM.Africa initiative, since integrated and interdisciplinary solutions are considered as key for a sustainable development. This means also developing advanced training and educational concepts for local artisans and manufacturers. The non-profit activities in Ghana of the Honorary Consul of Ghana in Bavaria and Saxony, Mr. Florian Wolfart, have been and will be supported by MSE.

1 Center for Combined Smart Energy Systems

Geothermal Alliance Bavaria (GAB)

Since 2016 three major Bavarian universities joined forces in the Geothermal-Alliance Bavaria (GAB): the Technical University of Munich, the Friedrich-Alexander University Erlangen-Nuremberg and the University of Bayreuth. The project is funded by the Bavarian State Ministry for Science and the Arts and coordinated by the TUM Munich School of Engineering. The aim of the Geothermal Alliance Bavaria is to further advance research in the field of deep geothermal energy in an interdisciplinary way with the goal of strengthening the use of deep geothermal energy as a local renewable energy source.

In order to replace the energy of phasing out technologies, alternate ways of providing energy have to be explored. In southern Bavaria, in the so called Molasse Basin, conditions to utilize deep geothermal are exceptionally good. However, a variety of research questions need to be addressed to improve finding, extracting and utilizing the energy stored in the deep reservoir in an efficient and economical way.

The key research topics of the GAB partners include to better understand the deep geothermal reservoirs, increase the operational longevity of geothermal plants, design efficient and flexible power plants, develop and implement tools to monitor power plant operations and to better understand the geological characteristics of the petrothermal reservoirs in northern Bavaria.

In addition, a joint Master's program on Geothermal Energy (GeoThermie/GeoEnergie) was established in the project. The program commenced in the winter semester of 2017/18.

The GAB-project is organized in five subprojects, which try to cover all aspects of a deep geothermal project. A schematic diagram of the research fields is presented in Fig. 1.

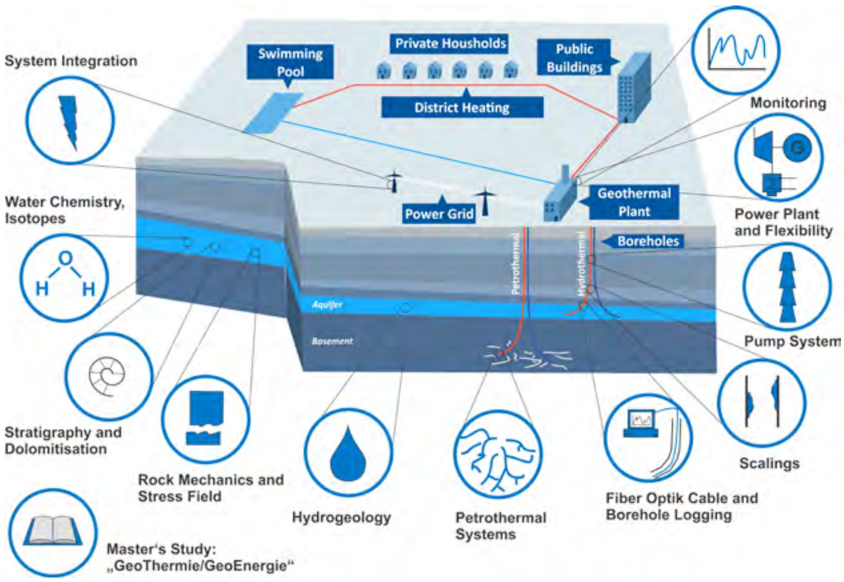

Fig. 1. Schematic overview of the addressed scientific questions within the Geothermal Alliance Bavaria. Source: Geothermal Alliance Bavaria, TUM.

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Within the past few years the Geothermal-Alliance Bavaria produced important scientific results. However, new research questions arose and existing questions have expanded. To investigate those new research topics and to serve as continuous contact for the national and international geothermal community and the public, the project management is currently working on securing funding for a second term.

The overall research objectives for the second funding term can be summarized as follows:

- Sustainable heat energy transition by intelligent use of deep geothermal systems
- State-wide use of geothermal energy using enhanced geothermal systems
- Sustainable thermal water production
- Social aspects for a save technology

Scientific subprojects

Characterization of the hydrothermal reservoir

The subproject “Characterization of the hydrothermal reservoir”, which is led by the Chair of Hydrogeology at TUM, focusses on the systematic investigation of local and regional variations within the deep seated Malm aquifer in southern Bavaria, with regard to geophysical, geomechanical, geostructural and hydraulic properties.

In the past years our researchers worked on minimizing the geothermal drilling success risks in the Molasse Basin and to understand uncertainties in reservoir engineering and in the long-term effects of deep geothermal operations. One milestone is the planned installation of a fiber-optic cable in a geothermal plant of the Stadtwerke München – the first of its kind – which will provide a unique data-set of the reservoir. Similarly geotechnical analysis of the reservoir-rocks in combination with analysis of the borehole logs will further increase the understanding of the reservoir.

Operational safety of the thermal water cycle

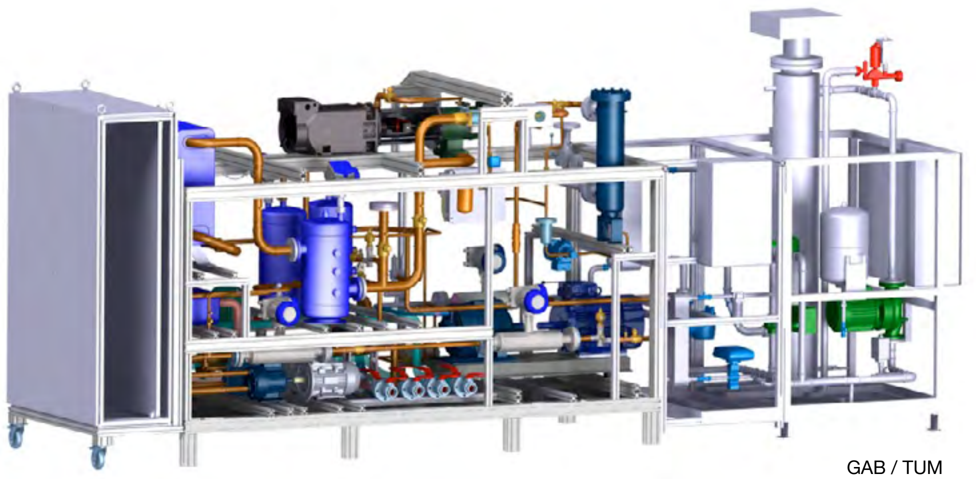
The thermal water cycle is the centerpiece of every deep geothermal operation. The main challenges are to increase the longevity of the electric submersible pump (ESP) and to understand the hydrochemical properties of the thermal water under certain pressure and temperature regimes which often cause several operational challenges in different plant components.

These two challenges are tackled firstly by the former MSE research group “Control of Renewable Energy Systems (CRES)”, which is now part of the Munich University of Applied Sciences with Prof. Dr.-Ing. Christoph Hackl. The group focusses on the operational stability of the ESP and the development of sensor-less monitoring systems. Additionally a lab-scale prototype of a pump motor was developed and the electrical control system was modeled.

Secondly, the Institute for Hydrochemistry at TUM investigates the formation kinematics of scalings within the thermal water cycle using an innovative hydrogeochemical modelling approach. For the first time the formation mechanisms of carbonate scalings within the thermal water cycle were identified.

Efficient geothermal power production

At the Chair of Energy Systems at TUM researchers work on identifying and implementing ways to optimize the potential in terms of efficiency and flexibility of geothermal power plants in a large-scale test rig. The focus lies on efficiency enhancing designs of the Organic Rankine Cycle (ORC) process in combination with suitable working fluids, as well as possibilities of flexible heat decoupling and the provision of balancing power by geothermal combined heat and power (CHP) plants (Fig. 2). In future electricity market scenarios, the provision of balancing power can be a new source of revenue for geothermal operations. Therefore, the possibilities and technical requirements are examined and tested at the TUM-ORC test rig (following the CAD-figure). A new generation of working fluids (i.e. Hydrofluoroolefines (HFO)) show great potential due to their low environmental impact (low global warming potential) and have been tested in more detail in practice.



GAB / TUM

Fig. 2. Technical drawing of the ORC pilot plant. Source: Geothermal Alliance Bavaria, Chair of Energy Systems, TUM.

The department of Engineering Thermodynamics and Transport Processes (LTTT) of the University of Bayreuth is responsible for the dynamic simulation of geothermal power plants to efficiently interconnect variants of electrical power and heat production. In addition, the LTTT is optimizing heat exchangers using computer simulations and specifically designed and developed lab-prototypes.

Another aspect of this subproject is the estimation of the economic potential of stored deep geothermal energy within Bavaria, which is carried out at the Chair of Renewable and Sustainable Energy Systems at TUM. The research group is taking into account not only the characteristics of the geological reservoir, such as temperature and hydraulic permeability, but also the heat demand of selected and representative Bavarian communities as well as the technical and economic capacity of selected plants and the topology of existing district heating networks.

Monitoring

The power plant is a crucial component to generate revenue by producing electricity. Thus, an enhanced plant operation with high efficiency and availability can improve the profitability of a geothermal power plant significantly. An unplanned shutdown of the plant generally causes high losses through lack of current revenues. Therefore, a software-based monitoring tool for geothermal power plants is developed at the Chair of Energy Systems at TUM to optimize the plant operation.

The overall objective of the subproject is to first evaluate the operation of the geothermal plant by developing a software-based online application for operational monitoring. This enables operators to detect deviations in plant operation early and allows them to take appropriate countermeasures. By comparing current operational data with past operating conditions, changes due to wear and tear can be identified beforehand to allow for predictive maintenance measures. Another aspect of this subproject is to develop methods to determine the optimal time for acidification of the pump. This has positive effects on the ecology and economy of a geothermal operation.

PetroTherm

As of now, only the deep seated aquifer in southern Bavaria is used for deep geothermal development in Bavaria. However, the potential of deep geothermal development can be significantly raised by exploiting the heat reservoir in dry crystalline basement rocks. To do so, it is necessary to improve the understanding of the underground of northern Bavaria, where these dry crystalline systems are present.

Therefore the GeoZentrum Nordbayern of the Friedrich-Alexander-University in Erlangen-Nuremberg undertook a large scale 2D seismic survey in northern Bavaria in 2018 to explore the deep underground and identify the reasons for the existing heat flow anomaly in this region. This survey is especially important because the underground in northeastern Bavaria is not well understood and underexplored, compared to the southern regions of Bavaria which benefited from extensive oil and gas exploration during the last century.

GAB / TUM

Vibro-truck during 2D-seismic campaign. The reflected signals are collected by geophones and reprocessed later. Source: Geothermal Alliance Bavaria, FAU.

Apart from the seismic survey, researchers concentrate on the structural geology, including estimation of geomechanical properties of the potential geothermal reservoirs by geomechanical testing.

Master's program geothermal energy

The joint Master's degree program organized by FAU and TUM offers a broad range of subjects associated with all aspects of geothermal energy research and started in the winter semester of 2017/18. The Master's program addresses to students from engineering sciences, geosciences or students from other natural sciences. The courses cover the geological and geophysical basics of exploration, reservoir characterization of hydrothermal and petrothermal reservoirs, the economic background, basics in thermodynamics, legal aspects of mining in Germany as well as public relations and basics of citizen science.

Additional third-party funding

The chairs and working groups, which are collaborating together within the GAB, are engaged in several associated projects and research-topics and are working together with other research facilities and/or partners from the industry. These associated projects provide additional input to the work carried out by the GAB.

For example, members of the GAB, under project leadership of the Munich School of Engineering, successfully applied for a research project funded by the German Environmental Agency. The project focusses on the integration of geothermal power and heat in existing systems and the possibilities to increase the flexibility of geothermal power plants. The project commenced in November 2016 and was completed by spring of 2019.

Seedfunding

Together with the scientific advisory council of the GAB, the GAB funded a total of twelve research projects in 2017, 2018 and 2019 with a maximum funding of 50.000 € for participants all over Bavaria. The seed funded research projects range from e.g. investigating acoustic sensors to monitor the electrical submersible pumps (ESP) to the development of a web-based seismic monitoring app for the urban areas of Munich.

Project management

In addition to the scientific work of the GAB partners, a project management team is established at the Munich School of Engineering. One of the main tasks of the project management team is to link the partners of the GAB with associated partners and geothermal operators in Bavaria to form a deep geothermal research network. This is achieved by organizing events to exchange ideas and actively participating at major conferences in the field of deep geothermal research. An example is the GAB's knowledge transfer event, a meeting, which which was carried out for the third time in March 2019. So far, these events did experience great interest and anticipation of the geothermal community. The topics of the past three events were: "Induced seismicity", "Exploration risk" and "Above-ground facilities and district heating networks". At the annual "Praxisforum

GAB / TUM

- **Visit of the geothermal plant Kirchstockach. In the foreground a drill bit can be seen, in the background the geothermal power plant. Source: Geothermal Alliance Bavaria, TUM.**

GAB / TUM

- **Opening of the exhibition on geothermal energy during October 2017 to December 2017 at ZEI. Source: Geothermal Alliance Bavaria, TUM.**

Geothermie.Bayern", the GAB manages and organizes a GAB Science Forum and at the German Geothermal Congress the GAB organizes its own Workshop about scalings and corrosion. At the upcoming Geothermal Congress 2019, which will take place in Garching, the GAB will be co-organizer for the first time with own forums and workshops.

In addition, the project management team is responsible for developing communication strategies towards the public, organizing public outreach, acts as a consultant towards policy makers and national and international research program representatives. For example the GAB team represents the deep geothermal technology at the energy summit meeting organized by the Bavarian Ministry of Energy and Economics and is in charge for the Bavarian Energy usage plan.

Project leader and head of the project management team at the Munich School of Engineering is Dr. Maximilian Keim. Research Associates are Dr. Markus Loewer and Ferdinand Flechtner, M. Sc.. Team assistant of the project team is Stephanie Hopf, B. Sc..

Multi-Energy Management and Aggregation Platform (MEMAP)

In connection with the ongoing energy transition in Germany, attention has lately been shifted to the building sector to reduce the energy demand, increase system efficiencies and to better integrate renewable energies through sector-coupling. Buildings and their system technologies shall no longer only be passive heat and electricity consumers, but also be able to offer services to the energy system in form of flexible decentralized energy generation and storage capacities in connection with intelligent demand side management. The progressive coupling of heat and electricity as well as interfaces to other sectors, such as mobility, makes this task even more complex. This forces a shift of the perspective away from individual buildings to a network of buildings in the context of the overall energy system. The multi-energy management and aggregation platform (MEMAP) project addresses these challenges and develops an aggregation platform that connects multiple buildings through their local Energy Management Systems (EMS) with different energy needs and requirements, thereby unlocking the potential of energy efficiency to increase.

Since the start of the project in 2017, a series of energy management control approaches has been developed for applications in urban energy systems. Firstly, a model predictive control (MPC) approach with a central linear optimization model was developed for the MEMAP platform. The first implementation was realized in MATLAB and then migrated to Java, where it is continuously improved and upgraded. The algorithm shifts production of heat and electricity to the most energy efficient plants and utilizes the physical interconnections between the individual generation units and storages to be operated for the benefit of the building community. The linear model is currently being expanded to accommodate a mixed integer formulation for plants with restricted production capabilities. In addition, analyses on concepts and technical aspects of innovative district heating networks allowing for the bidirectional exchange between participants in a compound were initiated to further investigate the approach of sector-coupling by means of prosumers connected to each other and to expand the energy management capabilities of the MEMAP to such a system.

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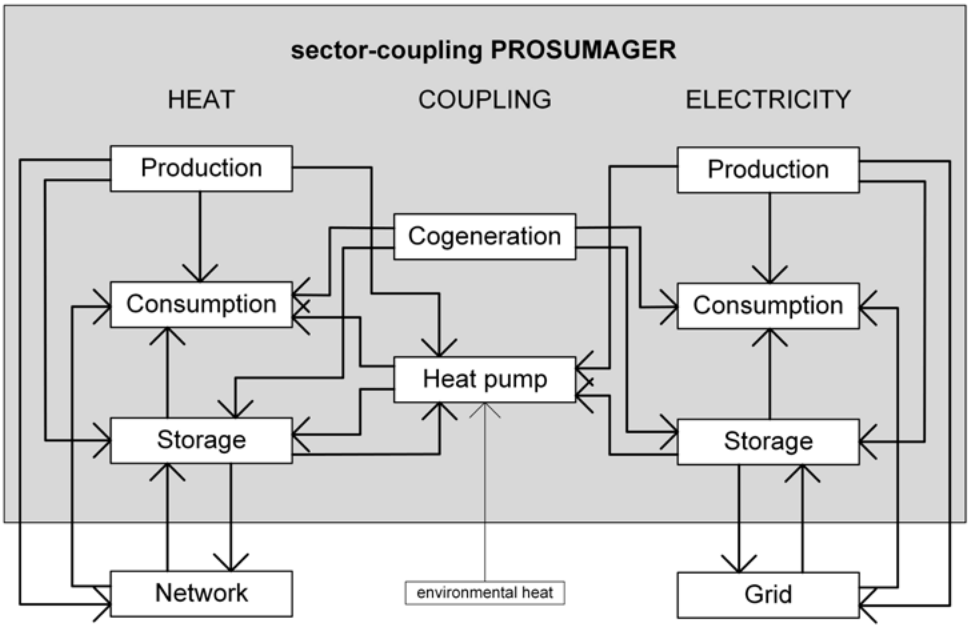

Fig. 1. Illustration of possible energy fluxes concerning a prosumager and its system environment

The proposed MPC approach was successfully tested in a co-simulation environment. The test case of a five house district will be replicated in the CoSES laboratory to finally run the MEMAP platform in a Hardware in the Loop test.

In line with the MPC approach, generalized component classes with according data models were developed for the possible installations (e.g. demand, volatile generation, grid or other coupling systems) that could be considered in respective energy systems.
At the same time, these data models specify the interface between the individual EMSs of the real devices and the optimal control algorithm performed on the platform. The actual communication is realized on the OPC Unified Architecture (OPC UA) standard. For this, an OPC UA server was set up and a stable connection between the platform and distributed EMSs was established. Currently, data from measuring equipment installed in a test area in Riemerling (near Munich) is exchanged in real-time via the OPC UA. Fig. 2 shows the hierarchical control structure between the governing MEMAP platform and the EMSs enabled by the OPC UA protocol to connect the interfaces.

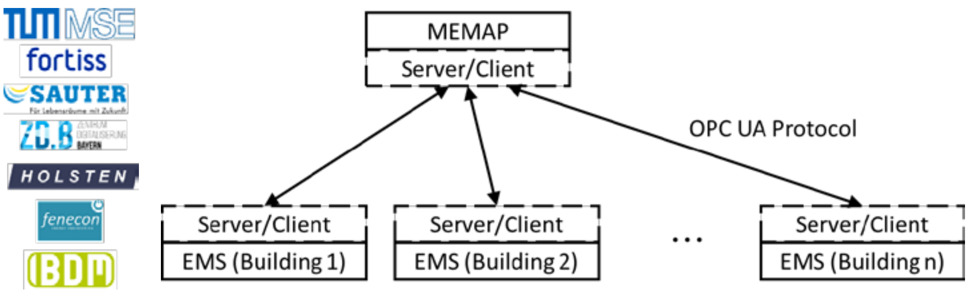

Fig. 2. Hierarchical control and communication structure between the MEMAP platform and individual EMSs of participating buildings

Additionally, several machine learning based control algorithms have been developed and tested to identify helpful applications for the MEMAP platform. As an example to overcome the need of expert knowledge to parameterize subsystem dynamics, one algorithm employs MPC to control the dynamics of a floor heating system. The control law is derived using an imperfect model of the house dynamics. In order to compensate for the model error, a Gaussian process (GP) is employed to model the unknown dynamics using measurement data taken during the control process. The GP model is hence updated online, which leads to an improvement in control performance with the number of available measurements. The proposed approach has been tested using an EnergyPlus house model, and an improvement in control performance was observed . Currently, a publication based on these results is in preparation. Furthermore, reinforcement learning and neural networks for control of volatile generation with storage and operation of a residential heating network has been investigated.

As the MEMAP project is one of the first projects to be tested in the CoSES laboratory, the assembling and testing of the laboratory infrastructure was supported by the MEMAP team. The first steps towards planning the integration of the MEMAP platform into the CoSES infrastructure were initiated and first simulation results are expected in 2019. Furthermore, the implementation of the MEMAP platform and the research project was represented at various industry events and research conferences. Among them, the project team is following the research initiative “EnergieWendeBauen” organized by the Projektträger Jülich, where researchers share their latest results on energy optimal buildings and city quarters.

EnEff:Stadt-Verbundvorhaben: Aggregationsplattform zur gebäudeübergreifenden Optimierung der Energieeffizienz, Teilvorhaben Modellierung, Optimierung und Simulation Energiesysteme: FKZ 03ET1413B. The project is funded by the German Federal Ministry for Economic Affairs and Energy.

Project duration: 01.06.2017-31.05.2021

TUM.solar

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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, chemistry, and electrical engineering. 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.

Organization of TUM.solar

TUM.solar is headed by Professor Müller-Buschbaum. TUM.solar covers the whole “value chain” from energy transformation up to energy storage and hereby aspects of basic physical-chemical processes up to application-related questions such as the construction of prototypes. 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 for mega cities. Furthermore, new materials allow alternative production processes leading to considerably lower 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 efficiency. Examples like photo-chemical reduction of carbon dioxide and water splitting are aspects which can drive to the so-called “green technologies”. In 2017 and 2018 the PIs working at TUM.solar were Prof. Dr. Thomas Fässler (CH), Prof. Dr. Katharina Krischer (PH), Prof. Dr. Peter Müller-Buschbaum (PH), Dr. Harald Oberhofer (CH), Prof. Dr. Karsten Reuter (CH), Prof. Dr. Ian Sharp (PH) and Prof. Dr. Martin Stutzmann (PH).

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 from the electrochemical reduction of carbon dioxide to solar fuels, integrated photo-catalytic semiconductor devices, electronic structure description of nanostructured electro- and photocatalytic systems, stabilizing hybrid organometal halide perovskite films against moisture, nanoscale heterogeneities and charge-selective interfaces for efficient and stable halide perovskite photovoltaics, synthesis of inverse opal structured mixed Si/Ge, and theory-based extraction of design rules for organic semiconductors.

Electrochemical reduction of carbon dioxide to solar fuels

The Krischer group obtained considerable progress in understanding the mechanism of electrochemical CO_2 reduction on both Pt electrodes in pyridine containing electrolytes and pyridine functionalized Si electrodes. In particular, an unexpected impact of the electrolyte pH was found. In a fundamental study of the role of protonated pyridine during CO_2 reduction on Pt electrodes, it was shown that pyridine is reduced to piperidine in acidic and neutral pH while in alkaline electrolytes pyridine is stable with respect to reduction reactions. Furthermore, it was demonstrated that in the literature the catalytic properties of pyridine for CO_2 reduction were overestimated. Also when pyridine is grafted (i.e. covalently bound) to a Si surface, it is protonated under acidic conditions. This leads to a positive surface charge, which can be used to tune the electron affinity and thus the band bending at the surface for a selected redox reaction. A strong decrease in overpotential was found for the hydrogen evolution reaction. At neutral or basic pH values there are no changes in the electron affinity and also no enhancement of the hydrogen evolution reaction was found. Furthermore, Si samples were investigated, which were decorated with Au nanostructures using lift-off nanoimprint lithography. Reducing the size of these structures leads to an enhancement of the activity of the samples for water splitting (see Fig. 1). The experiments suggest that this enhancement can be traced back to a bifunctional reaction mechanism at the three phase boundary silicon oxide / gold / electrolyte. The details of this bifunctional mechanism are subject of current research.

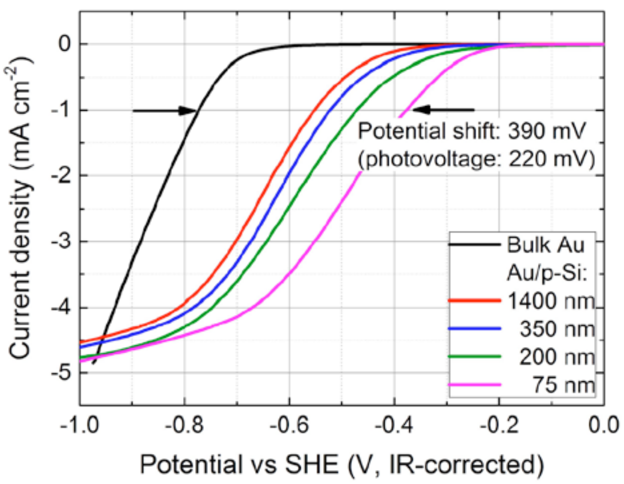


Fig. 1. Linear Sweep Voltammograms of p-Si electrodes covered with different nanostructures of Au or a continuous Au film in buffered $KHCO_3$ electrolyte saturated with CO_2 under illumination with 444 nm wavelength. A decreasing structure size leads to a drastic reduction of the overpotential (Potential vs. Standard Hydrogen Electrode).

Finally, for an improved investigation of gaseous reaction products from CO_2-reduction a novel cooling trap for electrochemical mass spectrometry was developed and built. The new setup has a considerable lower background signal of water and CO_2 than the old one, which exhibited background levels typically found in electrochemical mass spectroscopy. Detection limits of products are now in the order of 100 ppb.

Integrated photo-catalytic semiconductor devices

The Stutzmann group dealt with the development of integrated photo-catalytic semiconductor devices using a combination of commercially available high efficiency light-emitting diodes (LED) based on the InGaAlN materials system with well-defined GaN nanostructures grown by area selective molecular beam epitaxy (see Fig. 2). Unpackaged InGaN-LED wafers were provided by the company Osram Opto Semiconductors and served as the optically active substrate for the growth of GaN nanowires, nanowalls, and nanogrids. These nanostructures were defined with nanometer precision by electron beam lithography and enable an almost complete design freedom concerning the exact position of the nanostructures on the substrate as well as their lateral size and their height. This design freedom is used to optimize the coupling of light emitted by the LED underneath into specific optical modes of the nanostructures on top for potential applications in photo-catalysis. To investigate systematically the coupling efficiency between the LED and the nanostructures, they have performed numerical simulations of the optical properties of our devices for different periods, sizes and heights of the nanowires and nanowalls. These simulations were then validated and confirmed by quantitative experimental measurements on real device structures. Possible future applications of the devices are envisaged in the area of photo-catalytic reactions such as CO_2-reduction using organic molecules or other catalysts attached to the surface of the GaN nanostructures, which act as highly efficient optical antennas to deliver the light from the integrated LED to the photo-catalytic sites with minimal losses.

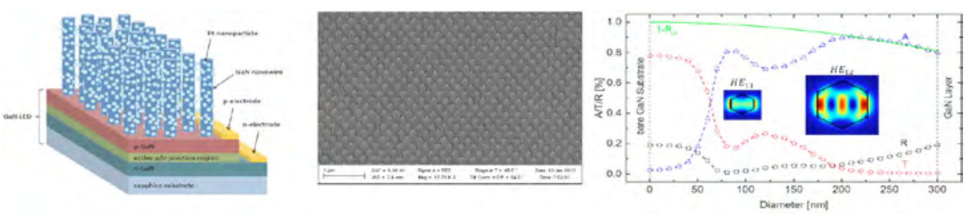


Fig. 2. Left: schematic picture of the proposed integrated photo-catalytic device consisting of a commercial InGaN light emitting diode, functionalized with GaN nano-antennas to funnel light to the photocatalytic centers attached to the antenna surfaces. Middle: Scanning electron micrograph of a periodic array of GaN nanowires grown on an LED substrate. Right: Numerical simulation results for the absorption (A), transmission (T), and reflectance (R) of such a nanowire array as a function of the nanowire diameter

Electronic structure description of nanostructured electro- and photocatalytic systems

The electronic structure theory calculations employed in the Reuter group aim at establishing a mechanistic understanding of fundamental reactions in the photo- or electro-catalytic generation of sustainable fuels (solar hydrogen, CO_2 reduction). Especially for selectivities in the CO_2-reduction, this requires a description of solvation effects beyond the state-of-the-art. Therefore, their work concentrated on further developing implicit solvation models and their implementation in modern density-functional theory program packages with a sufficiently high numerical efficiency to enable calculations of nanostructured systems. For such systems, an additional key issue is the uncertainty of the structure of the active sites. This uncertainty generally dictates calculations of the reaction energetics for a larger number of potential structural motives. The correspondingly multiplied computational effort can only be tackled by further increases in the numerical efficiency. For this, they advanced a machine learning approach (Sure Independence Screening and Sparsifying Operator, SISSO) for this context, which now allows to determine quickly the energetics of important reaction intermediates at diverse adsorption sites from one electronic structure calculation of the clean surface only. On the basis of these methodic improvements, ongoing work focuses on systematic mechanistic calculations. Here, a first application heralds that explicit kinetic barriers in a solvation environment can now also be considered.

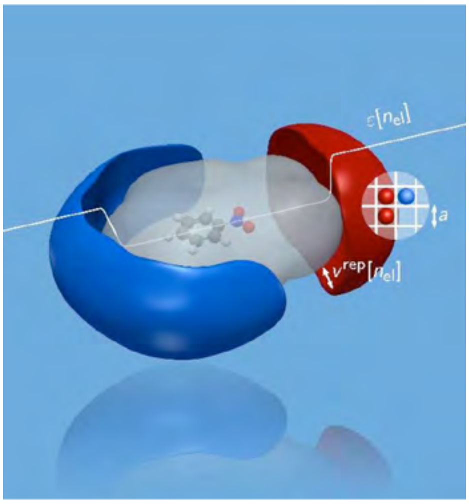


Fig. 3. Representation of the ionic electrolyte charge density as obtained within a Poisson-Boltzmann implicit solvation model

Stabilizing hybrid organometal halide perovskite films against moisture

Recently, hybrid organometal halide perovskites have attracted very high attention in the field of next generation solar cells due to their promising photovoltaic properties and resulting high power conversion efficiencies (PCE). These hybrid perovskites are usually of the form (MA)[PbX_3] (MA=$CH_3NH_3^+$; X=Cl^-, Br^- , or I^-), and by precisely tuning composition and thin film morphology only a few years of optimization have led to PCEs exceeding 22 %. Although progress in device efficiencies has been remarkable, lead–halide perovskites have two main drawbacks: the toxicity of the water-soluble source of lead and the instability of the material to atmospheric moisture. Therefore, research focusses on improving the moisture stability of the lead perovskite, however, the process of the water uptake itself is not deeply addressed. Due to the high sensitivity of $CH_3NH_3PbI_3$ to water, it tends to hydrolyze in the presence of moisture, leading to the degradation of the perovskite at a critical humidity of 55 %rh, which could be observed by a remarkable color change from dark brown to yellow. Using the grazing-incidence small angle neutron scattering (GISANS) technique and introducing D_2O vapor, the Müller-Buschbaum group probes the kinetics of water uptake of perovskite films at 30 °C and 40 °C, and follows the structure evolution of the perovskite films. The use of deuterated water gives the unique possibility to detect water inside the perovskite films. The moisture stability of a conventional MAPI film is tested in a plain film and one with a 2D protection layer (MAPI\2D). Surprisingly, all films showed degradation and a stronger degradation is observed in the film with protection layer (see Fig. 4). However, model fits of the data reveal that only the smallest structures in the MAPI\2D deteriorate, and as they are not present in the plain MAPI film, it can be interpreted as the 2D layer being “sacrificed” while the 3D perovskite film underneath is preserved. This important finding helps to understand the protection mechanism of the capping layer.

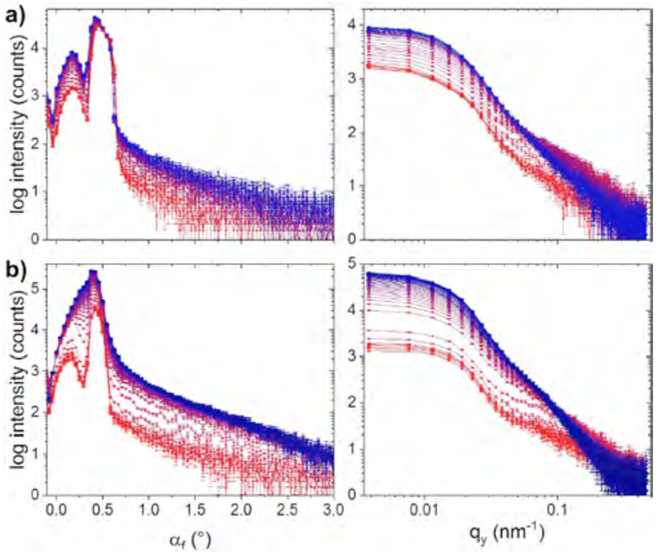
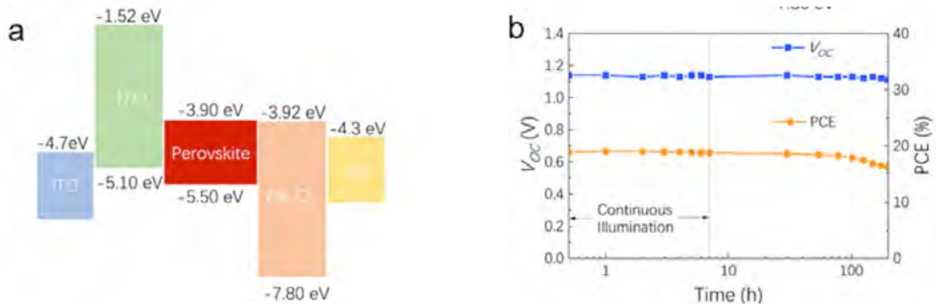


Fig. 4. In-situ GISANS data collected for (a) MAPI and (b) MAPI\2D. In the vertical line cuts on the left the position of the Yoneda peak only changes for the latter. However, morphological changes are obvious from the horizontal line cuts (right) for both samples.

Nanoscale heterogeneities and charge-selective interfaces for efficient and stable halide perovskite photovoltaics

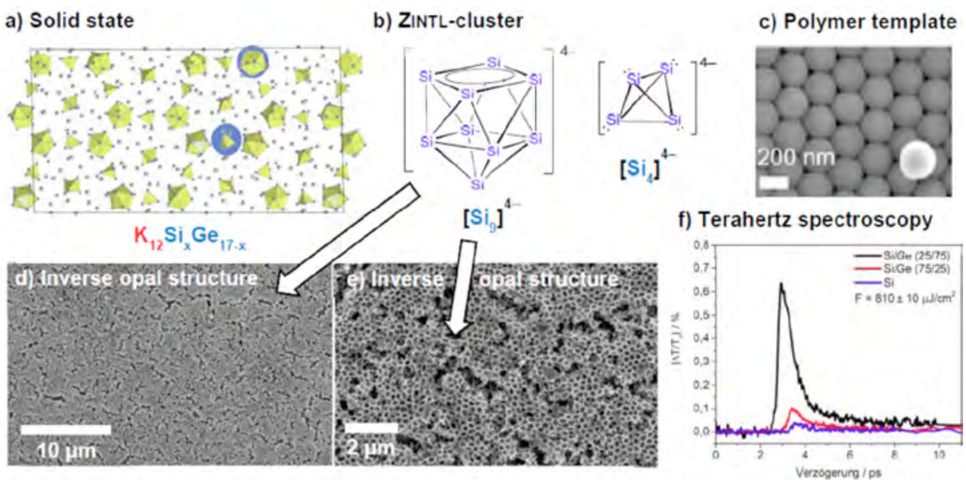
Hybrid metal halide perovskites have shown an unprecedented rise as active semiconductors for solar energy conversion and light-emitting applications. Despite tremendous progress in the field, there is a need for better understanding of mechanisms of efficiency loss and instabilities to facilitate rational optimization of semiconductor compositions, as well as their interfaces with selective contact layers. Starting from the device level and then diving into nanoscale properties, the Sharp group reviewed how structural and compositional heterogeneities affect macroscopic optoelectronic characteristics. Within this work, they provided a perspective on how unique feature of hybrid halide perovskite compounds – the propensity for these heterogeneities to evolve in space and time under illumination and applied electric fields – introduces additional challenges for characterization. Furthermore, they discussed how application of complimentary probes that can aid in correlating the properties of local disorder with macroscopic function, with the ultimate goal of rationally tailoring synthesis towards optimal structures and compositions. In related work, they contributed to the development of inverted planar heterojunction perovskite solar cells based on all-inorganic selective contact layers. Until now, the power conversion efficiencies (PCEs) of the few reported perovskite solar cells with this type of device structure were limited by relatively low photovoltages. The Sharp group proposed a new device structure comprising electron beam-evaporated nickel oxide and niobium oxide as the hole and electron selective contact layers, respectively (Fig. 5a). An open-circuit voltage of 1.16 V was achieved using a hybrid organic-inorganic perovskite with a band gap of 1.6 eV. The large photovoltage, enabled by the excellent charge extraction and blocking properties of the inorganic selective contact layers, led to a much improved and stable PCE of over 19.0% for this device architecture (Fig 5b).



■ **Fig. 5. Experimentally determined energy level alignment in perovskite inverted architecture solar cell with novel all-inorganic selective contact layers (a). Stable operation and large open circuit voltage of unencapsulated device under ambient conditions (b)**

Synthesis of inverse opal structured mixed Si/Ge

Initially, inverse opal structured amorphous (α-Ge) and crystalline (α-Ge) films were synthesized by the Fässler group from Ge_9-Clusters in solution. This process was then successfully transferred to other Zintl-phases in solution ($K_{12}Si_xGe_{17-x}$, Fig. 6a). In these ternary phases the desired ratio Si/Ge can already be achieved in the solid state (Fig. 6a) by adjusting the ratio in the anionic clusters (Fig. 6b). Incorporating a polymer template (e.g. PMMA, Fig. 6c) in the process that is removed after deposition of the Zintl-phase in solution enables the synthesis of inverse opal structured mixed Si/Ge as well as Si sheets (Fig. 6d, 6e). The resulting Ge, Si and mixed sheets are tested for their charge carrier mobility by terahertz spectroscopy (Fig. 6f). On top of that, functionalization of mixed clusters with silyl groups is possible. Silylated cluster compounds show a good solubility in a wide range of mildly polar as well as apolar solvents and therefore broaden the accessibility of cluster compounds as a basis for thin semiconducting sheets.



■ **Fig. 6. Synthesis of semiconducting films with inverse opal structure from Zintl-Phases in solution and evaluation of conductivity within these structures using terahertz spectroscopy**

Theory-based extraction of design rules for organic semiconductors

Research in the Oberhofer group concentrates on the discovery and improvement of organic semiconducting materials. To this end, they compiled, in a first step, a diverse database of existing organic crystals, examining each material for its applicability as a semiconductor. Out of this database, they derived, using modern methods of statistical analysis and machine learning, general design rules for organic semiconductors. At first, they studied the influence of different organic side-chains on the molecular reorganization energy, a parameter decisively determining the charge carrier mobility in the material (Fig. 7). They found a number of side-chains that, independent of their exact placement on the molecule, always improve the mobility. Yet, some of the groups they found have not been used at all in experiments. In the next step, they thus applied novel methods visualization to depict the chemical space of molecules available in their database. Thereby, molecular backbones are grouped according to their structural similarity into a network, which, among other things, highlights promising regions of chemical space. Some of these have not yet been captured in the database, which means that they had not been synthesized experimentally. The focus on previously synthesized materials thus brings both advantages and disadvantages. Although this guarantees the experimental accessibility of each crystal, the visualization of the Oberhofer group shows that this also leaves huge regions of chemical design space wholly unexplored. At the same time, the prediction of novel molecules is by far insufficient to predict semiconductor materials because the structures of the then formed crystals is just as important as the molecule itself. Thus, the Oberhofer group also contributes strongly to the development of new crystal structure prediction methods. Due to the chemical diversity of the crystals of interest, most such methods depend on quantum-mechanical calculations, which unfortunately are far too computationally intensive for their application to large databases. Thus, they also develop more approximate but computationally cheaper methods to be used in large scale data-production.

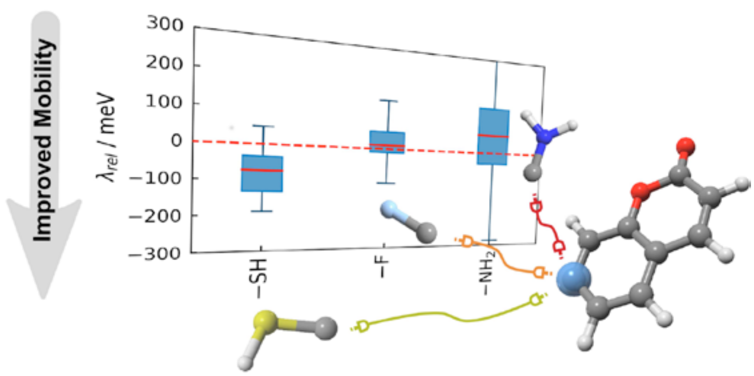


Fig. 7. Statistical influence of molecular side-chains on an important charge transfer parameter

ICER Project

Motivation

In the era of energy transformation and cost competitiveness of renewable and environmental-friendly energy technologies, integration and market design in complex modern energy systems remains one of the predominant challenges. The Munich School of Engineering is currently working together with the Nanyang Technological University (NTU) of Singapore to encourage international, multidisciplinary research in the field of energy. For this purpose, the international center of energy research (ICER) has been founded. Environmental sustainability, energy efficiency and emissions reduction are the main drivers of the R&D projects within ICER.

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A number of ten projects have been selected in an internal evaluation process, covering six energy-related areas, namely smart grids, advanced battery materials, solar cells, energy systems optimization, renewable energy & integration as well as lightweight materials. 20 chairs of both universities are involved and a similar number of doctoral students is working on these projects. The main goal is to develop innovative methods and technologies to improve energy systems all over the world and to bring international perspectives together for high-level research.

Detailed results from the projects and research outcomes have been published in more than

- 30 peer-reviewed and
- 25 non-peer-reviewed publications and
- 40 students have participated through internships and thesis.

Emphasis is put on technical and intercultural exchange between the two academic institutions. On the one hand, the technical cooperation is ensuring knowledge and technology transfer, on the other hand the intercultural exchange is facilitated by bilateral research stays and workshops. The doctoral students have been given the opportunity to spend several months in the joint partner's facilities as guest researchers, helping them to mature not only as professionals but also as individuals from the personal experience abroad.

The results of the projects lay the ground for future research activities. These results did act as basis for several proposals, which have already been submitted to funding entities. By this means, the ICER collaboration will be extended to contribute further to a renewable energy transition and shaping the optimal energy systems of the future.

Selected projects

In this section, two of the ICER projects are illustrated, which focused on research topics close to real engineering applications.

Optimal Power Flow Methods and System Architectures for Future Transmission Grids

The massive integration of renewable energy sources (RES) causes a rapidly increase in demand for transmission capacity in several countries. In Germany for example, the shift towards RES and the simultaneous decommissioning of conventional plants induces a growing energy surplus in the north and an energy shortfall in the south. This transformation of the generation structure determines the necessary capacity expansion of the transmission grid as a key issue in the energy transition. The required expansion measures are extensive and experience significant public and political opposition, particularly due to the implementation of new transmission corridors.

In this project, capacity expansion approaches that rely on the existing grid topology were investigated to mitigate the need for new transmission corridors, while inducing a structural transformation within the grid to facilitate a simplified and efficient solution of the optimal power flow (OPF) problem. This work resulted in the proposal of a hybrid grid architecture, which is a scheme for the systematic and system-wide conversion of selected Alternating Current (AC) lines to High Voltage Direct Current (HVDC) operation (Fig. 1). On the one hand, the hybrid architecture can increase the transmission capacity significantly and, on the other hand, it enables the solution of the nonconvex and NP-hard OPF problem with polynomial-time algorithms using semidefinite relaxation.

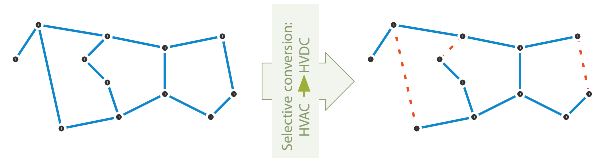

Fig. 1. Capacity expansion with the Hybrid Architecture

The project results show that the hybrid infrastructure has several advantages when compared to the existing grid:

- It can substantially reduce the impact of congestion and, therewith, considerably reduce the total generation costs compared to the original AC grid.
- It can liberate the trading of power by reducing the impact of congestion by achieving a remarkable "equalization" of the load marginal price (LMP) profile thanks to an improved utilization of generators with low marginal costs and the vanishing of upward peaks.
- It enables a more flexible integration of additional generation capacity into the system, beneficial for a continued inclusion of RES-based generation, where the location and capacity of individual expansion measures can be difficult to project.
- It has been shown in a proof of concept that a capacity expansion via the hybrid architecture can substantially reduce the need for new lines and potentially avoid the necessity of the much-debated and opposed north-south HVDC transmission corridors in Germany (Fig, 2).

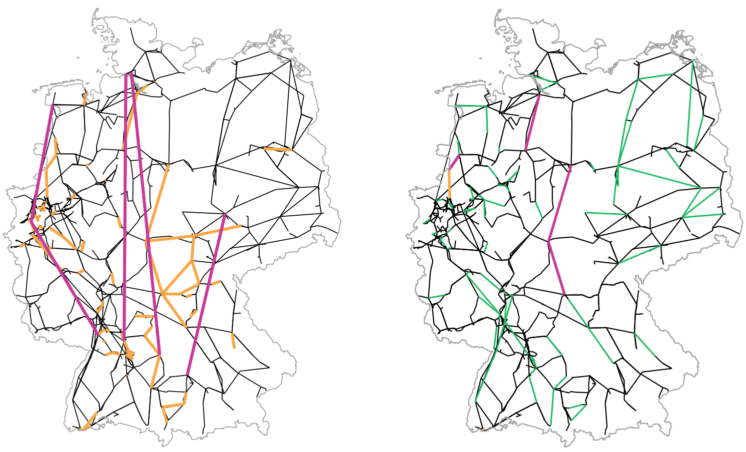

Fig. 2. Expansion strategy for the year 2030 of (a) the TSOs and (b) the hybrid architecture. Black lines are AC lines, while highlighted lines are AC lines in 2015 that were converted to DC operation in 2030 (green), new DC lines in 2030 (magenta), and new AC lines in 2030 (orange). In (b), only 6 of the 93 new lines in (a) are retained.

Low Grade Waste Heat Recovery for Enhanced Energy Efficiency in Heavy Industry – Organic Rankine Cycles

A significant amount of the consumed energy of industries and transportation systems is released to the environment as waste heat. For industrial applications, it has been estimated that 300 TWh/y of waste heat is available in the European Union, most of it lies in the range 100-200 °C, but significant shares also beyond, at higher temperatures. Organic Rankine Cycles (ORC) are a valuable technology to recover the available waste heat at low/medium temperatures and produce electricity or combined heat and power (CHP). ORC units are based on conventional power cycles, but make use of organic working fluids instead of water/steam. This is particularly advantageous to common water/steam power plants for heat source temperatures lower than 350 °C. A basic scheme of the ORC and the corresponding T-s diagram is shown in Fig. 3.

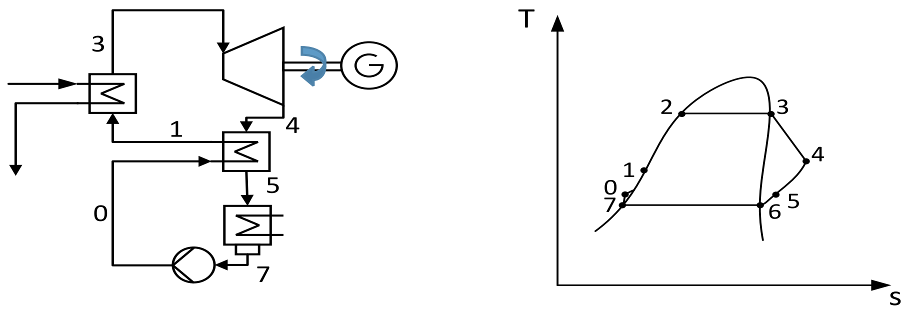

Fig. 3. Organic Rankine Cycle power systems: a) process flow diagram; b) T-s diagram

The project did investigate two major pillars: 1) component-level optimization, with particular attention to the ORC evaporator, being the link between the waste heat and the ORC 2) energy-system level optimization, where the integration of the waste heat source with the ORC as well as thermal storage solutions has been analyzed. As part of this project, a measurement device has additionally been built for the characterization of the waste heat source and a database of waste heat profiles has been developed. The device is readily available to extend the database continuously.

From the collected data on waste heat sources, it is clear that a significant amount of processes generate a fluctuating waste heat. This is particularly challenging for the design of the ORC, because a trade-off has to be found between nominal capacity and part-load operation. An integral optimizer considering design and off-design of the ORC has been developed. Taking as benchmark, waste heat recovery from a billet reheat furnace, it has been shown that specific costs can drop down to 37 % of an optimization considering only the nominal point. From the analysis, it is also clear that storage solutions might be advantageous, especially when the heat source is affected by large fluctuations in temperature.

In a component-level research, the dynamic design of ORC evaporators has been studied as a means to dampen waste heat source fluctuations. The response time of the evaporator can be determined from a limited amount of geometric parameters, which can then help the engineers to choose the desired component. Fig. 4 shows an exemplary performance map for a fin-and-tube evaporator. The best way to increase the thermal inertia is to increase the tube diameter while reducing either the number of tubes per bank or the length of the tubes.

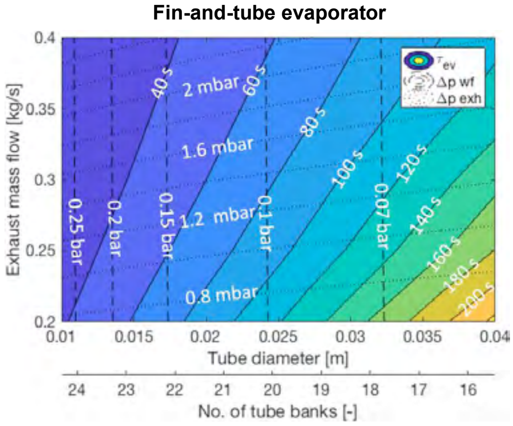

Fig. 4. Effect of exhaust mass flow and heat exchanger geometry on evaporator response time and pressure drops for different varying geometric dimensions and a 10% step increase in exhaust mass flow rate for fin-and-tube ORC evaporators

Future work in following projects will further validate the developed models with data from different plants in operation and innovative control strategies will be developed and tested in real plants to implement the solutions proposed in the presented project.

List of the ICER projects, thematic areas and chair principals involved

1. Smart Grids

Design and Control of Distributed Energy-Storage systems for the ASEAN Region (Prof. Jossen & Prof. Tripathi, Lead-PI[1]s Dr. Hesse & Prof. Tripathi)

Optimal Power Flow Methods and System Architectures for Future Transmission Grids (Prof. Utschick & Prof. Beng Gooi, Lead PIs Prof. Utschick & Prof. Fook Hoong)

2. Advanced Battery Materials

Interfacial Resistance in All-Solid-State Batteries: Fundamental Origins and Routes Beyond (Prof. Reuter & Prof. Yan Qingyu, Lead PIs Dr. Scheurer/Dr. Oberhofer & Prof. Madhavi);

Next Generation Electrolytes for Safer Batteries (Prof. Kühn & Prof. Madhavi, also Lead PIs)

3. Solar Cells

Charge Dynamics in Perovskites: Time-Resolved Infrared and Photocurrent Spectroscopy (PD Dr. Iglev & Prof. Soci, also Lead PIs);

Dye-Attachment to Photo-Electrocatalysts at Liquid-Liquid Interfaces: Tags, Control and Sensitization (Prof. Reuter & Prof. Michel-Beyerle/ Prof. Gurzadyan, Lead PIs Dr. Scheurer/Dr. Oberhofer & Prof. Madhavi);

Printable Perovskite Photovoltaics: Processing-Property Relationships through In-Situ-Morphology Measurements (Prof. Dr. Herzig & Prof. Mathews, also Lead PIs);

4. Energy Systems Optimization

Low Grade Waste Heat Recovery for Enhanced Energy Efficiency in Heavy Industry – Organic Rankine Cycles (Prof. Spliethoff & Prof. Romagnoli, Lead PIs Dr.-Ing. Wieland & Prof. Romagnoli);

5. Renewable Energy & Integration

Wind Turbines for Monsoonal Climates and Rare Extreme Conditions (Prof. Bottasso & Dr. Srikanth);

6. Light Weight Materials

Robust and Affordable Carbon Composite Tidal Turbine Blades (Prof. Drechsler & Dr. Srikanth, Lead PIs Senior Research Engineer Hibbard & Dr. Srinkanth);

1 **Principal investigators**

EVB Research Fellows

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The project Energy Valley Bavaria was funded by the Bavarian State Ministry for Science and the Arts as a lighthouse project for energy research. Amongst individual research projects, dedicated to increase the dynamics of conventional power plants to complement renewable energy integration, research fellows have been appointed for strategic key topics in between the project duration from 2013 to 2018. The research fellows have been equipped with substantial starting-grant and the right of self-reliant PhD supervision within MSE. This was unique at TUM at that time.

The research groups did address the following future topics

1. Organic Photovoltaics (Prof. Dr. Eva M. Herzig, now University of Bayreuth)
2. Energy Efficient and Smart Cities (Dr. Vicky Albert-Seifried, now Fraunhofer ISE)
3. Control of Renewable Energy Systems (Prof. Dr. Christoph Hackl, now University of Applied Science in Munich)

The huge success of the research fellows and their research groups is accentuated by the impressive amount of publications. During the last years, 44 peer-reviewed journal papers have been published and 78 conference contributions have been made. Beyond this, the research group leaders have given 40 invited talks and contributed to book chapters and diverse other scientific contributions.
The visibility of the research groups with national co-operations to BESSY[1], DESY[2] and universities in e.g. Aachen and Freiburg is outstanding. Even more so on an international scale: USA (Berkeley, NIST[3]), Chile, South Africa, Singapore and Korea, to name only some of them.
In the following, the yearbook summarizes the research projects and addressed topics in order to acknowledge the scientific work of the research fellows and their PhD students.

Organic photovoltaics

Head: Prof. Dr. Eva M. Herzig (now University of Bayreuth)

Organic photovoltaic (OPV) solar cells, are made from organic materials and are solution processible. They can be solution-cast, spin-coated – or attractive for industry – they can be printed. These thin films of just about 100 nm thickness can convert light into electrical energy. The conversion of sun light into electrical energy in photovoltaic devices can be divided into the main processes of light absorption and excitation of charge carriers, the separation of bound charge carries into free charge carriers, followed by transportation to the respective electrodes. Recently, a new strand of solar cells based on hybrid organic-inorganic halide perovskites (PSC) further exploits the advantages of solution based processing and outstanding optoelectronic properties. For both types of material systems the physical properties like charge transport are strongly linked with their nanostructure.

[1] Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung
[2] Deutsche Elektronen-Synchrotron DESY in der Helmholtz-Gemeinschaft
[3] National Institute for Standards and Technology

The aim of the research group is the controlled manipulation of the nanostructure of printed solar cells based on organic and perovskite materials. For both material systems the nanostructure is key to the device performance. To allow large scale production it is necessary to firstly access the relevant structural information, secondly to understand the relevant structure function relationships and thirdly to controllably reproduce the relevant structural properties with large scale processing methods. The group therefore has developed a solar cell printer that can be used within x-ray set-ups to access the nanostructure. Additionally, this printer offers the precise control of several environmental parameters. Doing so, the structure formation can be tracked in-situ during fabrication and provides crucial information on the underlying structure formation processes. The obtained knowledge is utilized to optimize the fabrication process and improve the device performance.

Project: Constructing and demonstrating a setup for atmospheric control during in-situ x-ray scattering measurements

Investigator: Stephan Pröller

An important part of the recent achievements has been the development of an environmental control chamber surrounding our printer head for the deposition of organic active layers. With this, it is possible to slow down or accelerate the drying process without altering the processing temperature. This gives significant control over the drying process and is an important step in our research strategy. By employing a suitable solvent atmosphere during printing of organic thin films, we can further manipulate the nanomorphology evolution of the active materials in organic solar cells.

Project: Utilizing novel processing approaches to gain control in the molecular arrangement of semi-conducting materials

Investigator: Jenny Lebert

The project investigated processing approaches to in-situ polymerized organic materials for applications in organic solar cells. Examining and optimizing an in-situ polymerization approach enabled the development of a cheap and environmentally friendly method to produce insoluble, nanostructured thin films suitable for the application in organic solar cells. It was further demonstrated that the processing route can be exploited to control the molecular arrangement into non-equilibrium but trapped states that are beneficial for charge transport mechanisms.

Project: Accessing structural information to track structural evolution with material specific sensitivity

Investigator: Mihael Coric

Many organic thin film materials, particularly those with recent record efficiencies, have similar electron densities, resulting in similar scattering length densities and therefore low contrast conditions in measurements. With the help of resonant energies, it is possible to gain more information on the inner morphology of the examined film. This is achieved by choosing the appropriate energy, at which for example contrast between materials is maximized. Using x-ray energies around the absorption edge of sulfur, enabled to gain information about the composition of the film morphology by exploiting the resonance effect of the investigated organic material system.

Project: Following the perovskite crystallization in mesoscopic perovskite solar cells

Investigator: Oliver Filonik

The structural analysis of the perovskite crystallization during fabrication yields information on the impact of processing conditions of mesoscopic solar cells. For instance, the introduction of processing additives can be utilized to actively control the nanomorphology evolution during processing by changing the underlying crystallization mechanisms. This is of particular interest, because measurements show different routes of evolution that help to explain the ramifications on the resulting solar cell performance, while final static measurements do not have the capability of revealing the underlying processes during fabrication.

Project: Determining the influence of processing environment on the morphological perovskite evolution

Investigator: Margret E. Thordardottir

This project focused on investigating the effect of humidity on perovskite morphology formation. The objective was to provide insights into the crystallization process of methylammonium lead iodide within a mesoporous structure with a special focus on the impact of humidity. It contributed to the fundamental understanding, necessary for upscaling perovskite solar cell production. Exploiting time resolved x-ray scattering, the presence of intermediate phases prior the perovskite formation was found. Moreover, the changes in morphology evolution were linked to the performance variation of the fabricated solar cell devices.

Energy efficient and smart cities

Head: Dr. Vicky Albert-Seifried (now Fraunhofer ISE)

Cities as hotspots of activities and growths are one key to an energy efficient and sustainable future. The highly concentrated but yet diverse energy use patterns in urban areas offer great opportunities for energy savings, particularly through better coordination between the demands and different supply systems. The Energy Efficient and Smart Cities (EESC) Research Group was founded in 2013 within the Munich School of Engineering (MSE). The overarching aim of EESC is to harness this potential and to make cities more energy-efficient and carbon neutral through better integration of urban energy systems.

Over the past five years, EESC has undertaken a number of projects in collaboration with various research institutes, government organizations and industry partners nationally and internationally. Using advanced modelling methods supplemented by laboratory measurements, onsite testing and monitoring, EESC addressed a wide range of topics related to distributed energy systems including PV and solar thermal applications, electricity and thermal storages as well as power-to-heat, which are important to the global energy transition.

Project: Optimal integration of energy storage in future smart city energy systems

Investigator: Akhila Jambagi

The changes that are occurring within the energy sector such as greater penetration of distributed generation and the increasing electrification of the heating and transportation sector result in the need for more flexible energy systems. As a powerful provider of flexibility, electrical energy storage will play a much more significant role in future energy systems. The aim of this work was to investigate the most important aspects of the integration of energy storage and their effects on one another to create insight into how best to integrate energy storage in an urban context. The three research aspects were: i) operational strategies, ii) optimal planning, and iii) future markets and flexible pricing schemes.

Project: Integrating demand side management of residential heating systems in smart distribution grids

Investigator: Michael Kramer

Demand side management (DSM) strategies work by matching the current generation from renewable sources through short term adaptation of demand. The goal of this project was to set up a model to evaluate DSM-strategies on a building block or city quarter scale. The work focused on Power-to-Heat technologies, particularly heat pumps, and evaluated their benefits by optimizing electricity and heatconsumption in urban energy systems by application of distributed predictive control approaches. Beyond this the impact of high penetration rates of such technologies in electricity grids has been investigated. This work was partially carried out as a contribution to the project ESOSEG (Environment for Simulation, Operation and Optimization of Smart Energy Grids) funded by German Federal Ministry for Economic Affairs and Energy (BMWi).

Project: ESOSEG – Environment for simulation, operation and optimization of smart energy grids

Investigator: Akhila Jambagi, Michael Kramer

The project aims to develop and test a software module to support electricity grid operators in the grid planning. The software module allows for the analysis of existing power systems and the simulation of future scenarios so the grid operators can use the results as a basis for the optimization of investment decisions. The role of EESC is to perform optimization studies on two use cases: i) development of a storage sizing algorithm and ii) a demand side management operational algorithm.

Project: Network design and yield optimization of solar district heating systems for urban applications

Investigator: Daniel Beckenbauer

Multi-story residential buildings provide high potential for solar-assisted local district heating. Current research projects focus on the utilization of large collector arrays and seasonal storages. However, for retrofitting densely built-up urban areas, the feasibility of solar district heating is often restricted by the space availability for collectors and heat storages. Moreover, high storage capacities come with high investment and thus high heat production costs. These drawbacks impede the application of seasonal storage concepts in existing urban areas and hinder the dissemination of large solar thermal systems.

Project: Theoretical and experimental analysis of polymer-based solar thermal drain back systems

Investigator: Mathias Ehrenwirth

The aim of this project is to investigate a solar thermal drain-back system with polymeric collectors. Polymeric materials can significantly lower the manufacturing costs of solar thermal collectors and contribute to the cost-effectiveness of solar thermal systems. This project is a collaboration with the Institute of New Energy Systems at the Technische Hochschule Ingolstadt through the Applied Technology Forum program of MSE.

Control of renewable energy systems

Head: Prof. Dr. Christoph M. Hackl (now University of Applied Science in Munich)

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, the 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 Control of Renewable Energy Systems (CRES) research group.

Central research and teaching activities in CRES are modelling, 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 multilevel 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 was covered.

Main research foci were (i) nonlinear, switched and dynamical modelling 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. The research activities were not only limited to technological aspects but also included didactic or economic aspects.

Project: Robust control of large-scale wind turbine systems

Investigator: Christian Dirscherl

The rising amount of wind power in the electrical power generation necessitates the need of detailed physical models of wind turbine systems (WTS), e.g. to improve their capability to meet grid code requirements and/or to participate in grid stabilization. Moreover, the rising size of WTS consequently results in an increasing nominal power. Concepts to cope with this increased power flow have to be investigated (e.g. parallel converter topologies). Besides the modeling, also the control of the WTS must be adapted and/or re-designed to allow a reliable operation even in unbalanced grid situation. To validate the derived models of WTS and the proposed control algorithms, simulations and experiments were performed.

Project: Enhanced control and model-based condition monitoring of electric submersible pumps in geothermal energy systems

Investigator: Julian Kullick

Electric submersible pumps are employed in deep geothermal energy systems in order to lift hot fluid to the surface. High production rates and harsh environmental conditions put severe chemical, thermal and mechanical stress on the hydraulic components leading to frequent pump failures. This subproject of the Geothermal-Alliance Bavaria project aims at improving the pump's lifetime and increasing the efficiency by developing (i) a model-based condition monitoring system for an a priori warning of imminent faults and (ii) robust, optimal and fault-tolerant control algorithms for the whole electrical drive system. A detailed dynamic model has been derived for the electrical and hydraulic components of the system which lays the foundation to tackle the remaining research objectives.

Project: Modeling and analysis of three-phase four-wire power systems

Investigator: Markus Landerer

The research project CleanTechCampus Garching deals with the development of an optimized, sustainable, transferable and holistic energy concept for the research campus Garching. The CRES sub-project is aiming at the modeling of a detailed three-phase four-wire dynamic system of the micro-grid to analyze optimal energy transmission, grid stability and current/voltage quality even under unbalanced loading conditions or grid faults. This approach involves the use of differential algebraic equations (DAE) for the modeling of energy generation, transmission and dissipation. Simulations and measurements were used to verify the derived models. The tasks focused on the three-phase four-wire modeling of nonlinear loads renewable energy, transformers, transmission cables and conventional electrically-excited synchronous generators.

Project: Condition monitoring and fault detection in large scale wind turbine systems

Investigator Korbinian Schechner

Condition monitoring (CM) and fault detection (FD) in wind turbines is necessary to avoid high maintenance and repair costs and to reduce long down times, where the system is not available for electricity production. So CD & FD systems help to reduce the costs and to increase the reliability of wind turbine systems. In contrast to the state-of-the-art, in this project, model-based observers of the electrical components are developed for CM and FD. These observers use only the available measurements and do not need additional sensors. For this, detailed dynamic models of the physical system capable of reduplicating the most common faults are required. The derivation of these models and the adjustment of the test bench for the required measurements was established. Finally, the developed CM and FD algorithms were tested in simulations and validated in the laboratory.

Project: Model-based optimal control of three-level voltage source inverters for anisotropicmachines

Investigator: Athina Birda

For an existing two- and three-level inverter, which feeds a permanent-magnet synchronous motor withhigh operating-point-dependent magnetic anisotropy, a control strategy will be developed, which willoptimally drive the system up to the magnetic saturation region. The requirements to be met are: (i) maximum drive efficiency, (ii) minimum torque ripple and (iii) minimum current ripple on the DC-link. The synchronous optimal modulation strategy is employed in order to optimize the motorperformance while the inverter is operated at low switching frequencies. Simulation and experimentalresults on the test bench will be made. Future work will focus on the three-level inverter topologyand the active balancing of the neutral point voltage.

Project: Robust and fault-tolerant low-level control of the electrical drive system of airbornewind energy systems

Investigator: Hisham Eldeeb

Airborne Wind Energy is considered a promising alternative to conventional wind turbines; owing totheir simple construction and operation at much higher altitudes. Accordingly, the amount ofproduced electrical energy per year could be significantly increased while the cost of electricityof this technology is expected to be much lower. One of the main challenges opposing such technologyis the need for a fault-tolerant electrical drive system to ensure safe and reliable operation. ThisPhD project is funded by the EU ITN H2020 AWESCO project (www.awesco.eu) and aims at developing afault-tolerant encoderless control for the adopted electrical drive system. Currently, two six-phase machines (reluctance and interior permanent-magnet synchronous machine) were designed and set up inthe laboratory to increase redundancy. Future steps are the detailed modeling and the development ofrobust and encoderless control algorithms.

Project: Modeling, simulation and control of a novel wave energy converter

Investigator: Simon Krüner

SINN Power is a Munich-based startup that develops a wave energy converter which supplies costumersat coasts all over the world with low-cost, reliable, sustainable electricity from ocean waves. Thewave energy converter consists of several point absorbers which are connected together in a grid-shaped structure. A generator unit in each point absorber module converts the movement of the pointabsorber in electrical energy. By implementing, an intelligent torque controller that optimallydamps the modules' movement, the generators can extract the maximum amount of energy from theincoming waves. The torque controller's performance was tested in a dynamic simulation environment.The next steps are (i) the implementation on a digital signal processor and (ii) its optimizationwith respect to enhancements in efficiency and accuracy.

Project: Computationally-efficient direct model predictive control of three-level neutral-pointclamped back-to-back converters for wind turbine systems with permanent-magnet synchronousgenerators

Investigator: Zhenbin Zhang

During this research project, computationally-efficient direct model predictive control (CE-DMPC)schemes for current/torque and power control of three-level neutral-point (diode) clamped (3L-NPC)back-to-back converters for wind turbine systems with permanent-magnet synchronous generators (PMSG)will be developed, implemented, optimized and validated on a hardware-in-the-loop system (emulatingthe whole wind turbine system). The developed algorithms will be implemented, tested and comparedwith convential DMPC on a FPGA/processor-based real-time system to measure and evaluate thecomputational load. Finally, the CE-DMPC schemes shall be combined with (existing) virtual fluxestimation methods to overcome the need of voltage sensors on the grid side.

Project: Operation strategies for biogas power plants for deterministic power generation

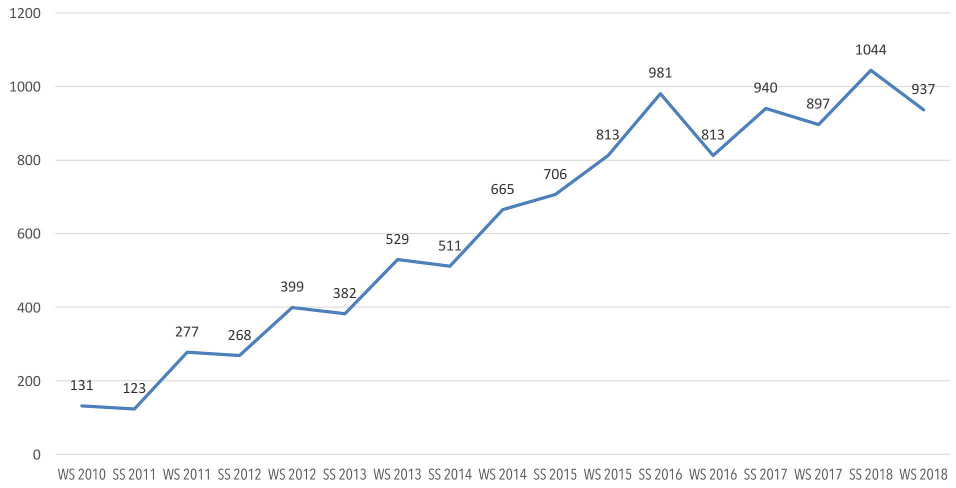
Investigator: Katharina Bär

The development of a control system for the operation of biogas based combined heat and power (CHP)units adjusted to the variable energy production of local PV power plants fed into the samedistribution grid feeder to avoid local overload of the transformer of the medium substationrepresents the main research issue of the project. Besides scheduling the CHP units according to theprices of EPEX SPOT SE day-ahead auction to maximize the turnover of the biogas plant operator bymeans of an optimization algorithm the operation control system focuses on the demand of thedistribution grid for the purpose of grid balancing. Furthermore, the control system includes anoptimized heat utilization concept to increase the total efficiency of the biogas plant. Physicaland technological constraints of the biogas and PV power plant, such as (i) capacity andavailability of the system components, (ii) process dynamics of the gas engine and generator and (iii) the limited gas storage volume are considered as well. In addition, a scientific monitoring ofa commercial biogas and PV power plant as well as the common grid connection point is carried out to validate the developed control system.

Facts & Figures

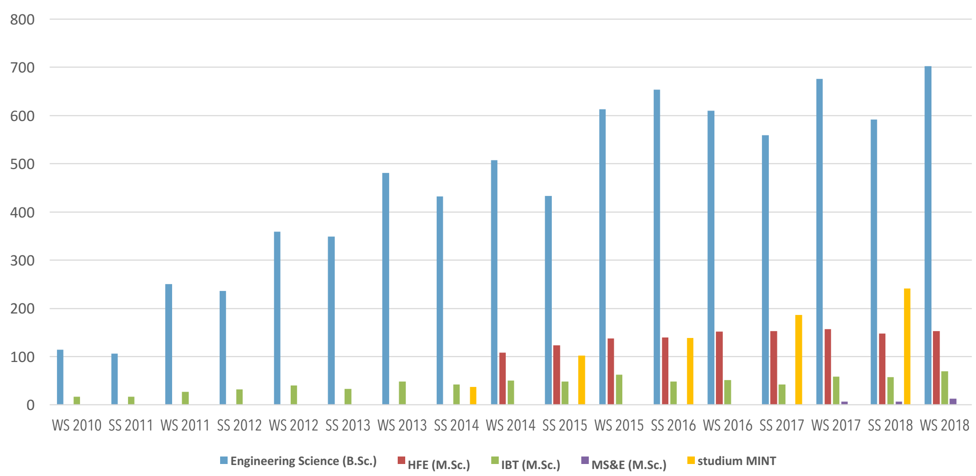
Facts & Figures

Students enrolled at MSE



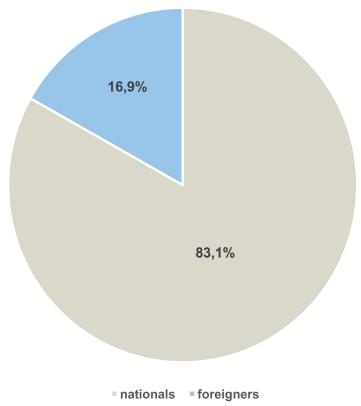
As of 13.11.2018. Source: TUMonline Studierendenmanagement

Students per program



As of 13.11.2018. Source: TUMonline Studierendenmanagement

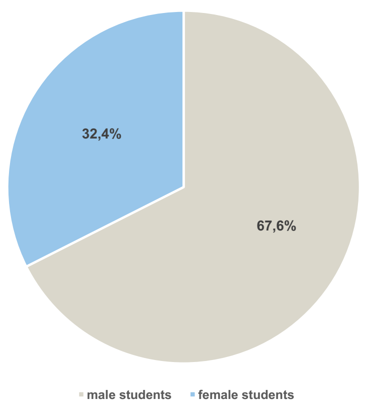
Proportion of foreigners



Relative share of foreigners per program	
studium MINT	12%
B.Sc. Engineering Science	17%
M.Sc. Ergonomics – Human Factors Engineering	11%
M.Sc. Industrial Biotechnology	21%
M.Sc. Materials Science & Engineering	45%

As of 13.11.2018. Source: TUMonline Studierendenmanagement

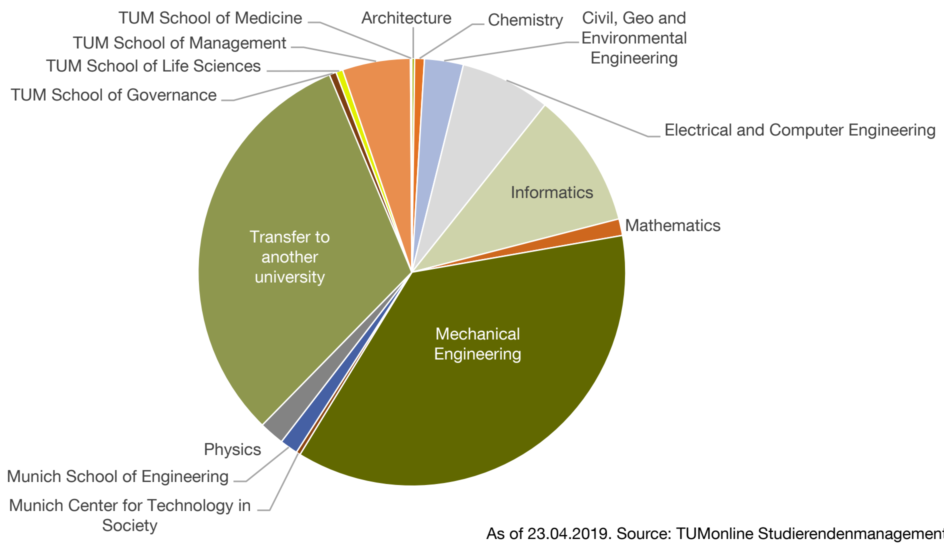
Gender proportion



Relative share of females per program	
studium MINT	33%
B.Sc. Engineering Science	27%
M.Sc. Ergonomics – Human Factors Engineering	52%
M.Sc. Industrial Biotechnology	54%
M.Sc. Materials Science & Engineering	9%

As of 13.11.2018. Source: TUMonline Studierendenmanagement

Engineering Science: Subsequent master studies



As of 23.04.2019. Source: TUMonline Studierendenmanagement

Selected Highlights from 2017/2018

Asbach / TUM

2017

June 26

TUM Research Center for Energy and Information – The Garching laboratory for research on the future of energy and home of the Munich School of Engineering is now complete and inaugurated.

June 30

Ceremony and farewell for all our graduates and tributes to our best lecturers and students.

J. Hofmann / TUM, Riegler

Dornmair / TUM

July 13

“Highlights in Energy Research” – 7th Energy Colloquium of the Munich School of Engineering with presentations and posters addressing broad energy research challenges and achievements.

October 15

Semester opening – We welcome the 2017 intake for our Bachelor’s program “Engineering Science”. May you have lots of fun, success and acquire a broad knowledge.

Nothdurft / FSMSE

October 16

Opening of the public exhibition “Geothermal Energy – Heat and Power From the Earth’s Interior”

Dornmair / TUM

2018

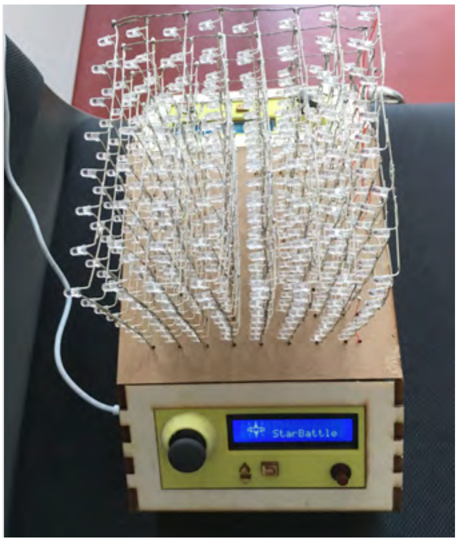
April 15

New student record for the orientation semester studium MINT: we welcome 245 new students for the STEM disciplines.

Kröss / TUM

July 5

Students of the orientation semester studium MINT showed the prototypes from their interdisciplinary hands-on project. Winner was an electrical 3D-Battleship game. The project is supported by Maker-Space GmbH and the scholarship foundation Zeidler-Forschungs-Stiftung.



Kröss / TUM

July 12

We celebrated our graduates, lecturers and outstanding students, the academic programs office and as a special moment our first scientist obtaining a doctorate at MSE.

J. Hofmann / TUM

J. Hofmann / TUM

July 29

With this year's topic "Advances in Energy Transition", the 8th MSE Colloquium centered on electrochemical energy storage, power generation and storage, renewable energies and the energy-water nexus.

Fischer/Wieland / TUM

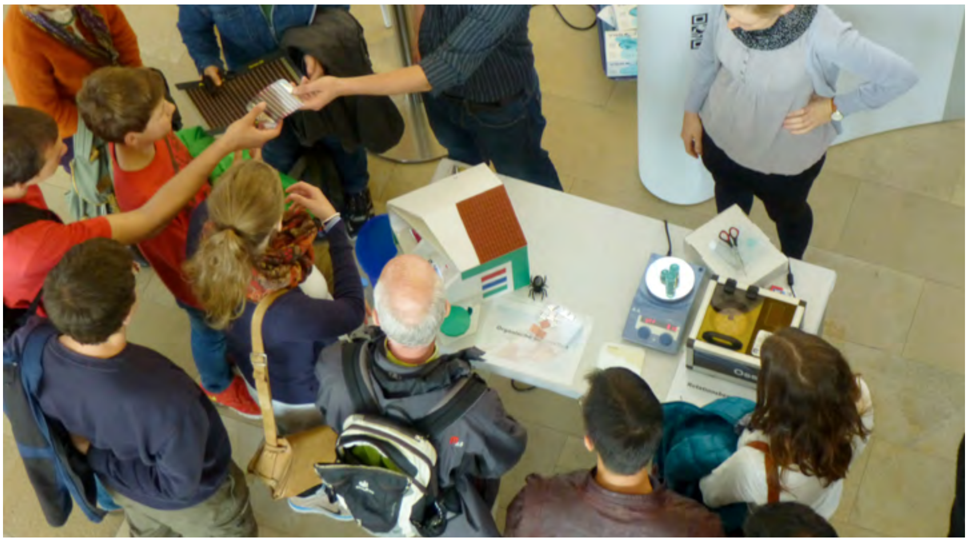
September 25

Students of the M.Sc. Human Factors Engineering while optimizing a Paralympic monoski at the Hintertuxer Gletscher.

Wörgötter / TUM

October 13

On the TUM open house day we had the opportunity to present our research and academic programs to the interested public.



Brunnbauer / TUM

October 24

We congratulate Dr. Künneth, the first to obtain a doctorate with honors at MSE in cooperation with University of Applied Sciences Munich.

C. Hamacher / TUM

November 29

Ko-op symposium and get-together for our scientists involved in our cooperation with universities of applied sciences.

Winklmaier / TUM

MSE Team

Heddergott / TUM

From left to right:

Mathilde Müller, Team Assistance
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
Prof. Dr.-Ing. Michael W. Gee, Dean of Studies
Dr. Katja Block, International Affairs Delegate, Recognition Management Master Programs
Robert Graner, Quality Management Officer
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

Former Team Members 2017/2018:

Dr. Christoph Neubert, General Manager
Birgit Reinbold, Head of Academic Programs Office
Martha Diglio Hupfer, Coordination M.Sc. Human Factors Engineering
Gunther Löfflmann, Quality Management Officer
Dr. Katja Kröss, Quality Management Officer
Sabine Kutscherauer, Team Assistance
Antje Asbach, TUMonline & IT

Portraits Welcome, p.7-9:
Eckert & Heddergott / TUM

Publications

Selected Publications

TUM.Battery

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Imprint

Publisher
Technical University of Munich
Munich School of Engineering
Lichtenbergstr. 4a
85748 Garching, Germany

Editors
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Dr.-Ing. Christoph Wieland
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Layout
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Cover Image
Dr. Andreas Battenberg

Printed by
Druckerei Joh. Walch GmbH & Co KG
Im Gries 6
86179 Augsburg

print run: 450

June 2019