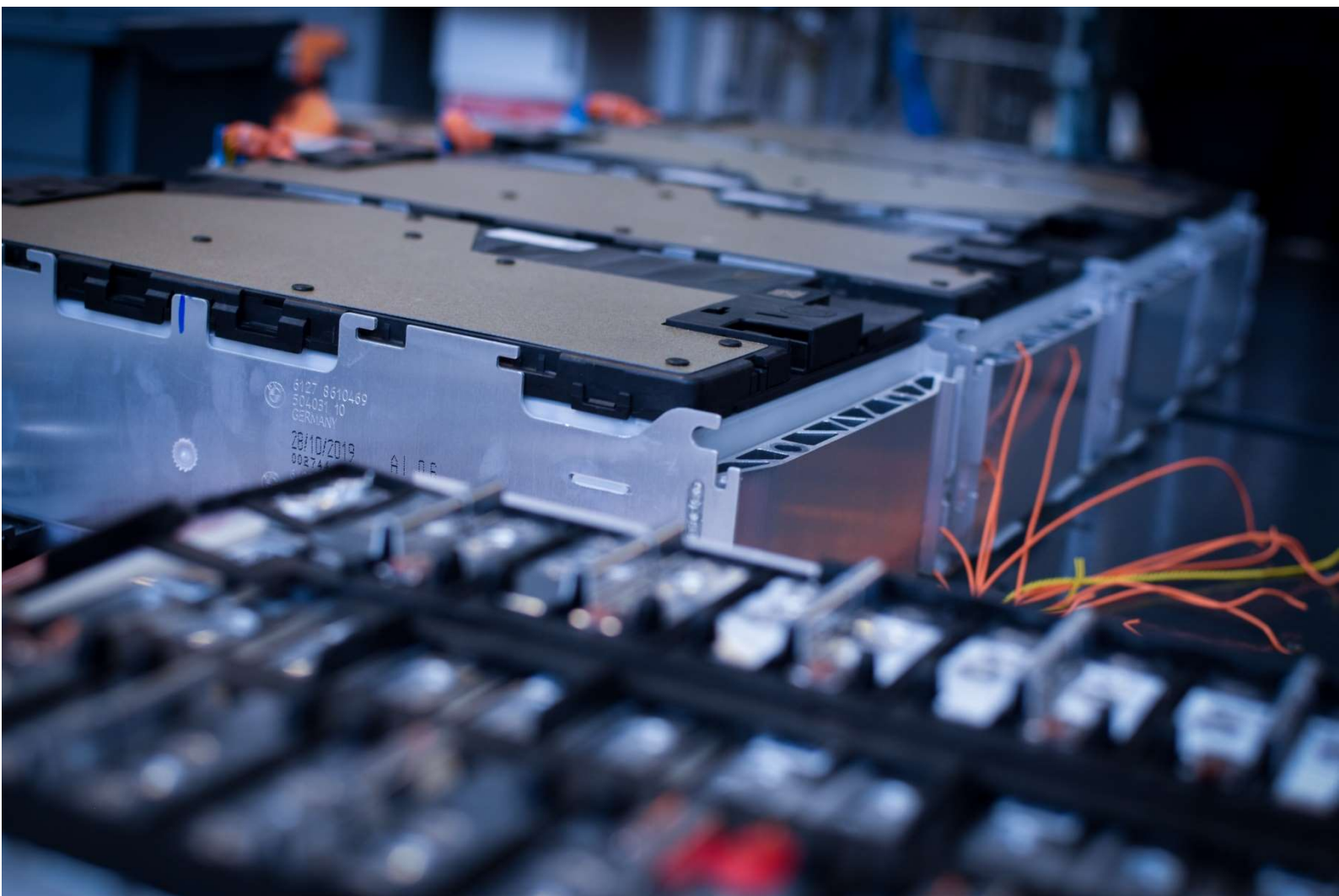


Module Handbook

Battery Materials & Technology (M.Sc.)

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General explanations

Sustainable energy supply solutions will be one of the most important challenges facing humanity in the coming decades. Questions in the field of e-mobility in particular pose a major challenge for Germany, as one of the countries with an extensive automotive industry. Well-trained specialists will be required to achieve top performance in research and development. Research in battery technology is highly interdisciplinary, requiring in addition to the basics of chemistry and materials science also good knowledge of electrical engineering and applied thermodynamics. Thus, high quality outcomes can only be achieved through the broad qualification of the graduates.

The core of the course is therefore a multidisciplinary educational approach from the natural sciences and engineering technology. Accordingly, the current program shares a fixed core curriculum with the predominantly German-taught Master's course in *Batterietechnik (Battery Technology)*.

However, the Master's course in *Battery Materials and Technology* focuses increasingly on teaching natural science skills in the field of battery technology. The qualification goal of the course builds on this and, in addition to the qualifications required for practical use in the field of engineering science, it is also intended to convey material competence and the necessary analytical methodology, above all with a decidedly natural science focus.

The aim of the core competence of the natural science-oriented English-language course is to be able to understand and process problems along the entire value chain of the battery system, applying a holistic, interdisciplinary approach. The scientific specifics of the Master's degree program take into account the requirements and qualifications needed and thus open up excellent career prospects for the graduates.

Modular structure and academic degree

The course is structured in modules. Using modules to organise the course of study, in combination with awarding credit points (LP) according to the European Credit Transfer System (ECTS), facilitates comparability and transferability of academic achievements within the European framework. The standard period of study for the course is four semesters with a total of 120 credit points (LP); one LP corresponds to an average student workload of 30 hours.

The programme of studies can be started in the winter semester or in the summer semester. Relevant competencies acquired at domestic or foreign universities can be recognised as completed study and examination credits upon an approved application. The university course is organised in modules, which usually comprise 5 credit points. 30 credit points are to be completed per semester.

The aim of this study course structure is to complement the teaching of missing foundational knowledge, to acquire sound skills on a broad number of battery-related subjects, and to establish a focus in specific research areas.

Pending the completion of all examinations in the required performance scope, the University of Bayreuth grants the academic degree of a Master of Science (abbreviated as: M. Sc.).

Types of courses

Knowledge transfer usually takes place using certain types of course teaching tools.

These include lectures (V), exercises (Ü), seminars (S) and practical trainings (P):

- **Lectures** (Abbreviation: V) deal with important topics of the respective field in a comprehensive presentation. They impart basic and specialised knowledge as well as information on methodology.
- **Exercises** (Abbreviation: Ü) are usually held in parallel with the lecture and serve to analyse the problem definition and to supplement and deepen knowledge on individual topics.
- **Seminars** (Abbreviation: S) work with research problems on selected individual issues. They serve to deepen the knowledge through independent study of scientific literature and impart training of oral and written presentation skills.
- **Practical trainings** (Abbreviation: P) convey apprentice experience with hand-on experiments in the laboratory. Scientific tests, suitable for the teaching of principles, are conducted by the students under guidance, evaluated, and often also presented in protocols.

Exam system

The examination consists of **the module exams** including the written master's thesis. The module exams cover the contents of the corresponding module. The exam type of the module is described in the respective module description. Any necessary further information on the examination type will be provided by the examiner at the beginning of each respective teaching units.

Typical exam types are written examinations, oral examinations, protocols, graded presentations or seminar papers (see §11 PSO).

Overview of the modules

Study outline

The students will deepen basic background knowledge from their respective bachelor's programs with a battery-specific focus and they will significantly expand their interdisciplinary knowledge in the battery sector.

The students will be brought to a common background level on the different disciplines of natural sciences and engineering by using the **alignment modules**.

The first joint interdisciplinary immersions are the **Battery systems technology 1** and **Battery materials 1** modules, in which the topic of battery is taught from the material and system side in order to enable a holistic understanding of the battery. **Electrochemistry 1** is the fundamental science for all internal processes within a battery cell. Only a sound education in this area enables a fundamental understanding of the basic processes. Accordingly, the corresponding modules take up a broad area in the first year of study.

The required **elective modules** (two from natural sciences and one from engineering science) facilitate the consolidation of individual knowledge along the diverse technological challenges of the entire battery value chain. They will lead to both specialisation and a holistic understanding of the battery. Further interdisciplinary studies follow, which are the modules **Battery materials 2**, **Battery systems technology 2** and **Electrochemistry 2**, to deepen the knowledge in battery systems technology.

A **seminar** module is also required, where current scientific papers are presented and discussed in front of a specialist audience.

The **research modules** allow students to apply their newly acquired knowledge creatively and critically to a current research topic from the field of Battery technology. One research module can be carried out externally, abroad or in the form of an internship with a company.

The degree program concludes with the **master's thesis**. It will be prepared based on a research plan. Practical and international periods are possible within the regular study period.

Module structure

	5 LP	5 LP	5 LP	5 LP	5 LP	5 LP
1	Individual alignment module A	Individual alignment module B	Individual alignment module C	Battery systems technology 1	Battery materials 1	Electro-chemistry 1
2	Elective module A	Elective module B	Elective module C	Battery systems technology 2	Battery materials 2	Electro-chemistry 2
3	Research module 1		Research module 2		Research plan	Seminar
4	Master thesis					

Module descriptions

Alignment modules

The alignment modules are used to create a common basis for the students taking into account their prior education. These are introductory modules on areas in which the students have not yet reached certification.

During the admission process, the alignment modules are individually assigned from the catalogue of alignment modules below (see next pages). Three alignment modules, totalling 15 LP (credits), are to be completed by all students. Alignment modules should be completed during the first year of study.

In some cases, additional modules can be assigned by the study program moderators as admission requirements, to complement further missing background courses.

Catalogue of alignment modules

Module title	Fundamentals of Mathematics for Electrochemical Energy Storage Systems
Responsibility	Junior professorship for Methods for Battery Management
Type of course	Lecture (2 SWS) and Exercises (1 SWS)
Desired learning outcomes	Overview of the advanced mathematical methods that are needed to address relevant problems in electrical energy storage systems. Ability to apply these methods with the aid of modern computational tools to fundamental problems in electrical energy storage systems.
Contents	Fundamentals and application examples for advanced mathematical methods. The course covers sequences and series, functions with multiple variables, complex numbers and functions, ordinary differential equations, differential equations systems, numerical methods for solving ordinary and partial differential equations, Fourier series, Laplace transformation. Using advanced computational tools (Python) to solve applied mathematical problems.
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	Lecture: 30 hours; Homework: 60 hours Exercises: 15 hours; Preparation and follow-up 15 hours, Exam preparation: 30 hours

Module title	Fundamentals of Physics for Electrochemical Energy Storage Systems
Responsibility	Chair for Theoretical Physics VII
Type of course	Lecture (2 SWS) and Exercises (2 SWS)
Desired learning outcomes	This course aims to give students an overview of basic concepts and tools of physics as they pertain to batteries and their materials. Skills and concepts acquired in the lectures will be deepened in the accompanying exercises.
Contents	<ul style="list-style-type: none"> • <u>Classical mechanics</u>: Newtonian laws, energy, conserved quantities, Hamilton formalism, crystallography, symmetries, phonons • <u>Electrodynamics</u>: Coulomb Potentials, Poisson equation, plate capacitor model, currents, magnetism, Maxwell equations in vacuum and matter • <u>Quantum mechanics</u>: operators, quantisation, Schrödinger equation, quantum uncertainty, chemical bonds, orbitals, electronic energy levels • <u>Thermodynamics and statistical mechanics</u>: temperature, thermodynamic potentials, Laws of Thermodynamics, heat capacity, thermal expansion, heat conductivity, diffusion
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	German/English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours Exercises: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 45 hours

Module title	Fundamentals of Inorganic Chemistry for Electrochemical Energy Storage Systems
Responsibility	Chair of Inorganic Active Materials for Electrochemical Energy Storage
Type of course	Lecture (3 SWS) and Exercises (1 SWS)
Desired learning outcomes	The objective is to refresh the basics of general and inorganic chemistry for students who had few ECTS in chemistry in their education. The course will provide all basic knowledge needed to later attend the courses in Battery materials. The focus of the course is on solid-state chemistry, i.e. the students will learn especially what governs the stability and properties of solids.
Contents	The course starts from the very basics of atomic structure and atomic models, to well understand the periodic system. Basic quantum mechanics will be discussed to go beyond the Bohr model to the Schrödinger equation. The structure principles for multi-electron atoms will then be clarified, as well as the Octet rule. The course will then cover bonding between atoms, starting from the ionic bonding. The Madelung constant and Born-Haber cycle will be studied. Covalent bonding and hybridization are covered next, including Lewis structures, electronegativity, polar bonds and VSEPR. The LCAO method will be shown for simple molecules. Secondary bonding will be briefly touched upon. Then solids will be discussed based on their electrical properties. Insulators, semiconductors and metals. The origin of the band structure in solids will hence be discussed. Important (close-packed) crystal structures are also discussed. The last lectures will refresh specific topics: i) solubility and acids/bases, and ii) chemical kinetics and diffusion (Fick's laws).
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	Lecture: 45 hours; Preparation and follow-up: 15 hours Exercises: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 30 hours

Module title	Fundamentals of Physical Chemistry for electrochemical Energy Storage Systems
Responsibility	Chair of Electrochemistry
Type of course	Lecture (2 SWS) and Exercises (1 SWS)
Desired learning outcomes	<p>Acquiring competence in the field of physical chemistry. Specifically, by the end of this course students should be able to:</p> <ul style="list-style-type: none"> • Discuss the laws of thermodynamics and how they can be used to describe chemical systems. • Apply thermodynamic principles to compute properties of chemical systems in an equilibrium state. • Discuss the kinetic model of gases, the process of diffusion and describe motion of ions in liquids. • Discuss the empirical kinetic laws and apply them to describe the simple chemical reactions.
Contents	<p>The lecture is divided in two parts: thermodynamics and kinetics. In simple terms thermodynamics dictates if a reaction can occur at all, whereas kinetics describes how fast (or slow) the reaction proceeds. The lecture will cover the following topics:</p> <ul style="list-style-type: none"> • Properties of ideal and non-ideal gasses • The first Law of Thermodynamics • Entropy, The Second Law • The Third Law, Gibbs Free Energy, and Chemical Reactions • Chemical Equilibria in Mixtures, Electrolytes • Chemical Kinetics: 1st and 2nd Order Reactions <p>If time allows, we will cover transition state theory and its thermodynamic aspects, i.e., the combination of thermodynamics and kinetics.</p>
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours</p> <p>Exercises: 15 hours;</p> <p>Exam preparation: 75 hours</p>

Module title	Fundamentals of Macromolecular / Organic Chemistry for Electrochemical Energy Storage Systems
Responsibility	Chair of Polymer Materials for Electrochemical Energy Storage
Type of course	Lecture (2 SWS)
Desired learning outcomes	The objective is to acquire competences and refresh knowledge in the field of basic macromolecular / organic chemistry. The lecture gives an overview of the most common polymer compounds discusses their synthesis, characterization, and properties.
Contents	<p>The lecture teaches the nomenclature of functional organic groups and gives an overview about where organic and polymer compounds are relevant in batteries. It briefly touches on the history of polymers and batteries, as well as the working principle of batteries and the most relevant key performance indicators.</p> <p>The core of the lecture revolves around basics of macromolecular chemistry, i.e., the structure of polymers, their synthesis, characterization, and properties:</p> <ul style="list-style-type: none"> • Definitions: degree of polymerization, number and mass weighted molecular weight, molecular weight distribution, and polymer topology. • Single chain models: chain conformations, ideal chains, random-walk-model, Kuhn-segments, persistence length, real chains, Flory Huggins theory. • Analytical methods: colligative methods, viscosity measurements, SEC, DLS/SLS, SAXS • Synthesis methods: step growth polymerization, chain growth polymerization, emulsion polymerization, • Synthesis examples for most industrially relevant polymers, high performance polymers, and specialty polymers. • controlled polymerization techniques: ionic polymerization, AROP, RAFT, ATRP, copolymers and polymer architectures. • Material properties: polymers in solid state, melts, and phase transitions, mechanical properties, testing and rheology, thermal analysis, DSC, DMA, TGA • polymer processing: extrusion, injection moulding, fibre spinning. • polymer recycling: metrics about plastic production and waste, recycling concepts and future perspectives biological and bio-based alternatives to the currently used petrochemicals • brief introduction to functional polymers, self-assembly, block copolymers, nanostructures, polymer electrolytes, conductive polymers, polymer coatings
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 90 hours

Module title	Fundamentals of Electrical Engineering for Electrochemical Energy Storage Systems
Responsibility	Chair of Electronics for Electrical Energy Storage
Type of course	Lecture (2 SWS) and Exercises (2 SWS)
Desired learning outcomes	Understanding of the physical electromagnetic effects occurring in electric resistors, capacitors, inductors, and transformers. Analyzing (node-voltage analysis) all kinds of electric networks containing voltage and current sources (DC and AC), resistors, capacitors, inductors, and transformers.
Contents	<ul style="list-style-type: none"> • The electrostatic field (i.e., electric charges and electric charge densities; Coulomb's law; Coulomb force; the electric field strength; the electric flux density and the electric flux; Gauss's law; field lines and equipotential lines; the electric potential; potential difference and electric voltage; work, power and energy; the electric induction and the electric polarization; the capacitance and the capacitor); • The stationary electric flow field (i.e., the electric current and the electric current density; Ohm's law in differential and integral form; conductivity and resistivity; the electric resistance and the electric resistor); • DC networks (i.e., ideal and real voltage and current sources; networks; one-port and two-port component; branch, mesh and node; Kirchhoff's circuit laws: Kirchhoff current law (KCL) and Kirchhoff voltage law (KVL)); • The magnetostatic field (i.e., magnets; the Laplace force; the Lorentz force; the magnetic field strength; the magnetic flux density, the magnetic flux and the magnetic total flux; Ørsted's law and Ampère's circuital law; the current linkage); • The electromagnetic field (i.e., Faraday's law of induction; Lenz's law; the self-induction; the inductance and the inductor; the inductive coupling and the mutual inductance; turns and windings; the transformer and the transformation ratio; Maxwell's equations); • AC networks (i.e., characteristic parameters of periodic signals; complex calculus with phasors and amplitude phasors; impedance and admittance; resistance und conductance; reactance and susceptance; active power, reactive power, apparent power and complex apparent power; power factor and displacement angle); • Transient states (i.e., continuity conditions in capacitors and inductors; analysis of networks with one storage element).
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours Exercises: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 45 hours

Module title	Fundamentals of Materials Science for Electrochemical Energy Storage Systems
Responsibility	Chair of Electrode Design for Electrochemical Energy Systems
Type of course	Lecture (2 SWS) and Exercises (2 SWS)
Desired learning outcomes	<p>At the end of the course, the students will be able to:</p> <ul style="list-style-type: none"> • Apply the core principles of materials science to analyze ceramics and polymers. • Analyze the mechanical responses and phase diagrams of materials. • Critically evaluate the use of various characterization techniques for the analysis of materials. • Integrate knowledge of structure, properties, and processing for a comprehensive view of materials science and engineering.
Contents	<p>This course introduces the core principles of materials science and engineering, emphasizing materials structures such as atomic and crystal arrangements, and the connections between microstructure elements like grain size and defects, and properties such as strength and ductility. A special focus will be on the behavior of ceramic and polymer materials, including phase transformation and the optimization of their physic-chemical attributes. The course also offers foundational knowledge about the composition, properties, and fabrication of ceramics and polymers. Modules encompass ideal / real crystals, defects, doping, diffusion, mechanical properties, phase diagrams, microstructure, and characterization. The curriculum's blend of fundamental and practical insights serves as a comprehensive foundation for future studies in materials science. The course concludes with a review module that synthesizes the key concepts, providing a perspective on this complex and evolving discipline.</p>
Admission requirements	None
Availability frequency / Duration	Every semester/ 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours Exercises: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 30 hours</p>

Module title	Fundamentals of Signals and Systems for Electrochemical Energy Storage Systems
Responsibility	Chair of Systems Engineering for Electrical Energy Storage
Type of course	Lecture (2 SWS) and Exercises (2 SWS)
Desired learning outcomes	<ul style="list-style-type: none"> • perform classification of signals and systems • application of convolution for simple problems • understanding of Fourier-Series, Fourier and Laplace transforms and application to solving simple problems • explain the relationship between signals and systems • master different approaches to mathematically describe the output-input behaviour • explain the relationship between transfer function and complex impedance • perform time discretization of continuous systems • explain and apply the Nyquist-Shannon sampling theorem • apply the z-transform to simple problems
Contents	<p>The understanding of signals and systems is used in many specialized methods when dealing with batteries (i.e., impedance spectroscopy). This alignment module is intended to provide a basis for understanding basic modelling and simulation methods as applied to battery technology. It includes Fourier series, Fourier transform, Laplace transform in the application for the analysis of signals but also for the solution of differential equations. Basic signals like unit step, Delta-Dirac and pulse train are introduced. Hereby it becomes possible to switch between periodic and aperiodic signals, as well as between continuous-time and discrete-time signals and systems. Finally, the z-transform is introduced for discrete-time systems.</p>
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 15 hours</p> <p>Exercises: 30 hours; Preparation and follow-up: 30 hours</p> <p>Exam preparation: 30 hours</p>

Mandatory modules

The mandatory modules are Battery materials 1 and 2, Electrochemistry 1 and 2, and Battery systems technology 1 and 2. Each of these modules has 5 LP, for a total of 30 LP.

Moreover, two research modules and the master's thesis must be carried out. These must be related to the 'battery' topic. The subject will be selected by a professorship who is involved in the course of study.

The Research Modules 1 and 2 can be carried out at all professorships participating in the study program. Two different modules are not to be carried out in the same research group. One research module can be carried out externally, abroad or in the form of an internship with a company.

Battery systems technology 1

Responsibility	Chair of Electrical Energy Systems, Chair of Systems Engineering for Electrical Energy Storage Junior professorship for Methods for Battery Management
Type of course	Lecture (2 SWS), Exercises (1 SWS) and practical training (1 SWS)
Desired learning outcomes	The objective is to acquire interdisciplinary competence in the field of battery systems technology. The students will gain an overview of the structure and function, the properties and behaviour, the use and operation of battery cells. They will get to know engineering methods and system-related questions from different domains of battery technology.
Contents	In addition to the construction and function of a battery cell, the manufacturing of the cell will be presented as well. Parameters relevant to the operation of a battery, such as capacity or power, as well as status variables such as standby voltage or charge state are introduced. The students learn about methods of charging, testing and characterization of battery cells and gain initial insights into the modelling and ageing of batteries. Other key aspects are safety and sustainability with regard to battery technology. The students learn about safety-critical behaviour with regard to batteries and suitable measures for safe operation. The students will be presented with aspects of the battery life cycle from raw materials to recycling.
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 30 hours Exercises: 15 hours; Preparation and follow-up: 30 hours Practical training: 15 hours Exam preparation: 30 hours

Battery systems technology 2

Responsibility	Chair of Systems Engineering for Electrical Energy Storage, Chair of Electronics for Electrical Energy Storage
Type of course	Lecture (2 SWS), Seminar (1 SWS) and Exercises (1 SWS)
Desired learning outcomes	The objective is to acquire interdisciplinary competence in the field of battery systems technology. The students will gain an overview of the structure and function, the properties and behaviour, the use and operation of battery systems. They will get to know engineering methods and system-related questions from different domains of battery technology.
Contents	In addition to the general structure and function of a battery system, different topologies and architectures will be presented. Students will learn about the requirements of battery systems in applications such as in the energy grid or drive technology, as well as the degrees of freedom and fringe conditions of the design. Limits, parameters and state variables of battery systems are introduced, which play an important role in monitoring and battery management. Students get to know the components of a battery system such as sensors, electronics, power electronics, and charge regulators. They will get first insights into the methodology of state estimation, as well as the prognosis of performance, energy and service life, the mechanical design, and thermal management. Other aspects relevant for operation, such as ageing, failure, safety and functional safety of the battery systems, are introduced.
Admission requirements	Recommended: Alignment modules A to C.
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours Exercises: 15 hours; Preparation and follow-up: 30 hours Seminar: 5 hours; Preparation and follow-up: 25 hours Exam preparation: 30 hours

Battery materials 1

Responsibility	Chair of Inorganic Active Materials for Electrochemical Energy Storage, Chair of Inorganic Colloids for Electrochemical Energy storage
Type of course	Lecture (3 SWS) and Exercises (1 SWS)
Desired learning outcomes	Interdisciplinary acquisition of competence in the field of battery materials. The students will learn about the synthesis, structure and electrochemical properties of the most important electrode materials on the market, as well as those in the research stage. The course will focus on active materials.
Contents	Introduction to energy storage technologies, battery definitions and concepts, fundamentals of solid-state chemistry and material chemical concepts in the field of electrode processes and reactions, phase diagrams, cathode and anode materials (focus on electronic and crystal structure, synthesis, reactivity and stability), introduction to common separators and electrolytes.
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 45 hours; Preparation and follow-up: 15 hours Exercises: 15 hours; Preparation and follow-up: 15 hours Exam preparation: 60 hours

Battery materials 2

Responsibility	Chair of Inorganic Active Materials for Electrochemical Energy Storage, Chair of Inorganic Colloids for Electrochemical Energy storage, Chair of Inorganic Chemistry III, Chair of Polymer Materials for Electrochemical Storage
Type of course	Lecture (3 SWS) and Exercises (1 SWS)
Desired learning outcomes	Interdisciplinary acquisition of competence in the field of battery materials. The students will learn about the redox behaviour, structure and electrochemical properties of the most important electrode materials on the market, as well as those in the research stage. The course will focus on passive materials (polymers, separators, electrolytes) and analytical methods.
Contents	Passive components in battery systems. Polymers as binders, separators and active materials. Properties of polymers in batteries. Electrolytes and conductivity. Strengthening of concepts of redox chemistry and crystallography. XRD and NMR as key analytical methods for battery materials. Focus on operando analysis.
Admission requirements	Recommended: Alignment modules A to C.
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 45 hours; Preparation and follow-up: 15 hours Exercises: 15 hours; Preparation and follow-up: 15 hours Exam preparation: 60 hours

Electrochemistry 1

Responsibility	Chair of Electrochemistry
Type of course	Lecture (2 SWS) and Exercises (1 SWS)
Desired learning outcomes	<p>Acquiring competence in the field of electrochemistry. Specifically, by the end of this course students should be able to:</p> <ul style="list-style-type: none"> • Demonstrate how the electrochemical potential and chemical equilibria define the thermodynamic potential for an electrochemical reaction; • Discuss the validity and shortcomings of the Butler-Volmer equation to describe electrode kinetics; and be familiarized with alternate theories for describing electrode kinetics (Marcus' theory, Gerischer's theory and combinations / derivations thereof); • Understand and discuss the role of charge and mass transport in electrochemical systems; • Attain a general understanding of what happens (in terms of e.g. measured currents, concentration gradients, diffusion limitations, among others) when an electrochemical cell is pushed out of equilibrium via a step in the potential.
Contents	<p>The lecture will cover the following themes:</p> <ul style="list-style-type: none"> • Intro & Overview of Electrode Processes • Potentials and Thermodynamics of Cells • Kinetics of Electrode Reactions • Mass Transfer by Migration and Diffusion • Double-Layer Structure and Adsorption • Basic Potential Step Methods <p>The exercises related to the lecture content may be partially incorporated into the planned in-person active time of the module</p>
Admission requirements	None
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	1 st course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours</p> <p>Exercises: 15 hours;</p> <p>Exam preparation: 75 hours</p>

Electrochemistry 2

Responsibility	Chair of Electrochemistry
Type of course	Lecture (2 SWS), Exercise (1 SWS) and Practical training (1 SWS)
Desired learning outcomes	<p>Acquiring competence in the field of electrochemistry, especially in terms of methodology (both theoretical and practical). Specifically, by the end of this course students should be able to:</p> <ul style="list-style-type: none"> • Describe how linear and/or cyclic voltammetry can be used to characterize the thermodynamic and kinetic properties of an electrochemical reaction. • Describe how the method of impedance spectroscopy works and how it can be utilized to characterize solid samples as well as solid electrode-liquid electrolyte cells. • Discuss the similarities and differences between controlled potential and controlled current methods for characterizing electrochemical systems. • Discuss the advantages and short-comings of convection-controlled electrochemical methods (hydrodynamic electrochemistry) • Proficiency in the construction of three- and two-electrode cells and confident application of the methods described.
Contents	<p>The content of the exercises section will be partially incorporated into the planned in-person active time of the module. The practical training of this Module will be hosted in the Labs of the Chair of Electrochemistry. Possible experiments are as follows:</p> <ul style="list-style-type: none"> • Ionic conductivity determination of solid electrolytes (via impedance spectroscopy, two-electrode measurement) • Cyclic voltammetry of (quasi)reversible redox couples • Assembly and galvanostatic (constant-current) cycling of Li-ion coin cells • Double-layer capacitance characterization of inert electrolytes via cyclic voltammetry and impedance spectroscopy (three-electrode measurement) • Determination of electrochemical stability window of an electrolyte via stepwise voltammetry (two- or three-electrode measurement) • Rotating ring-disk electrochemistry: three-electrode measurement, calibration and determination of faradaic efficiency of generated oxygen.
Admission requirements	<p>For the Lecture and Exercise: None. For the Practical training: Pass the Electrochemistry 1 Module Final Examination, and an additional oral exam on the theory of the planned experiments. Recommended: Math Alignment Module and Physical Chemistry Alignment Module</p>
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours Exercises: 15 hours; Practical training: 15 hours; Exam preparation: 60 hours</p>

Seminar

Responsibility	Study programme moderator
Type of course	Seminar (1 SWS)
Desired learning outcomes	Presentation and discussion of recent scientific works in front of a specialist audience
Contents	Current scientific works from the field of battery technology are presented by the students and are placed into an overall scientific context. The seminar presentation is followed by an academic discussion.
Admission requirements	Recommended: Battery system technology 1+2, Battery materials 1+2, Electrochemistry 1+2
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	3 rd course semester
Language of instruction	English
ECTS credit points	5 LP
Course components <ul style="list-style-type: none"> • Attendance of the seminar during the whole semester • Independent development and presentation of a current scientific topic from the field of battery materials/battery technology • Followed by an academic discussion • The presentation is to be summarized in a graded seminar paper. 	
Module testing	graded seminar paper (30%) and presentation (70%)
Student work input in hours	Active time: 15 hours Preparation and follow-up: 15 hours Development of seminar presentation and paper: 120 hours

Research module 1 and 2

Research topics for the research modules can be chosen from a list which is published each semester before the start of the lecture period. Additionally, if students are interested in a particular research topic or research question, they can approach the relevant chair and request this as a research module. The research module can only be started if the student has earned at least 30 LP (credits). In particular, all alignment modules and three mandatory modules must have been passed.

One research module can alternatively be carried out externally, abroad or in the form of an internship with a company.

Responsibility	Chairs or professorships involved in the course of study
Type of course	Research module
Desired learning outcomes	Students should gain insight into the current research practice. In addition, they are to acquire experimental skills through independent laboratory work under guidance, and they are to practice team skills and train in presentation techniques.
Contents	The learning content relates to the current research projects of the Chair. The module includes experimental work, literary work, participation in work group seminars including their own presentation and the preparation of a protocol.
Admission prerequisite	Successful completion of all individual alignment modules and three mandatory modules is compulsory. (total: minimum 30 LP)
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	3 rd course semester
Language of instruction	English
ECTS credit points	10 LP
Module testing	graded protocol (75%) and graded presentation (25%)
Student work effort in hours per module	Practical work and evaluation: 200 hours; Preparation: 25 hours; writing: 50 hours; presentation: 25 hours

Research plan

Responsibility	Chairs or professorships involved in the course of study
Type of course	Written report and presenting the results to a specialist audience
Desired learning outcomes	This module will teach how to prepare a scientific research work, in particular with regard to the current state of research, taking into account the scientific literature as well as appropriate time and experiment planning.
Contents	An up-to-date literature outline should be drawn up before any experimental work is started, and the essential questions concerning the planned research are presented in relation to each other. A testing plan is to be established. Furthermore, the necessary instrumental prerequisites are to be clarified and the time and material requirements of the planned experiments subjected to a critical examination. A presentation and subsequent discussions will again serve to hone presentation skills and facilitate comprehensive feedback on the intended research.
Admission prerequisite	The successful completion of the individual alignment modules and the mandatory modules is recommended.
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	3 rd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	graded protocol and graded presentation
Course components	<ul style="list-style-type: none"> • Initial literature/ bibliographic survey related to the assigned topic • Presentation of the research plan to the working group • Written research plan
Student work input in hours	Active time: 30 hours Preparation and follow-up: 30 hours Exam preparation: 90 hours

Master's thesis

Responsibility	Chairs or professorships involved in the course of study
Desired learning outcomes	Ability to independently work on a research-relevant battery- related problem; practice written and oral presentation and communication techniques.
Contents	Written report on a current battery-related topic (master's thesis)
Admission prerequisite	Advanced study ability; passing exams for at least 40 LP credits (see examination and study regulations for this and other regulations).
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	4 th course semester
Language	English or German
ECTS credit points	30 LP
Module testing	Dissertation
Student work input in hours	Research, evaluation and written elaboration on the master's thesis Total: 900 hours

Compulsory elective modules

There are three compulsory elective modules to be completed, each 5 LP (credits). Two modules from the elective field of 'natural sciences' and one module from the field of 'engineering sciences' are to be selected.

The compulsory elective modules are to be chosen from a list of elective modules (see following pages).

The compulsory elective modules, each with 5 LP, are offered by the following professorships:

Engineering sciences

[You must select one compulsory elective module]

- Electronics of electrical energy storage
- Systems engineering of electrical energy storage
- Electrode design of electrochemical energy storage
- Cell design of electrochemical energy storage
- Electrical energy systems
- Functional materials
- Material process engineering
- Methods of battery management
- Business informatics and sustainable IT management

Natural sciences

[You must choose two compulsory elective modules]

- Electrochemistry
- Operando-analysis of electrochemical energy storage
- Inorganic active materials for electrochemical energy storage
- Polymer materials for electrochemical storage
- Physical chemistry I-III
- Inorganic chemistry II-III
- Macromolecular chemistry I-III
- Theoretical physics
- Inorganic Colloids for Electrochemical Energy Storage

Natural sciences

Module title	Colloids and Surfaces
Responsibility	Chair of Physical Chemistry
Type of course	Lecture (2 SWS) and Practical training (6 SWS)
Desired learning outcomes	The course includes advanced physical chemistry of colloids and surfaces, e.g. phase behavior, structure formation and dynamics of microemulsions; properties of nanoparticles; block copolymer micelles; formation of mesoscopic crystals; interface properties; "smart" interfaces; "confinement" effects in thin films and wetting effects.
Contents	<p>The lecture includes phase behavior of binary and ternary mixtures of water, oil and amphiphiles. Amphiphiles can be surfactants, lipids, block copolymers and colloids. The Helfrich concept of elastic bending energy is introduced. In addition, mixed polymer-surfactant systems are discussed. The scattering methods used to study these systems are briefly discussed (e.g. SANS). This part is followed by a section on interfaces with a focus on polymer films and polyelectrolyte multilayers. The relevant experimental methods such as atomic force microscopy (AFM), scanning tunneling microscopy (STM), scanning near-field optical microscopy (SNOM) and ellipsometry are presented.</p> <p>The practical training will deal with the synthesis and characterization of colloidal particles and the use of microscopy and light scattering methods. Furthermore, the phase behavior of a ternary system (surfactant/oil/water) will be investigated with small angle X-ray scattering. Finally, colloids or polyelectrolytes will be assembled on surfaces and interfaces. The resulting structures are investigated with AFM and ellipsometry.</p>
Admission requirements	none
Availability frequency / Duration	Every Winter semester (WiSe) / 1 semester
Recommended semester	2 nd course semester
Language of instruction	German / English
ECTS credit points	7 LP
Module testing	Written or oral examination (60%) and Practical training (40%)
Student work input In hours	<p>Lecture: 30 hours; Preparation and follow-up: 15 hours</p> <p>Practical training: 90 hours; Preparation and follow-up: 45 hours</p> <p>Exam preparation: 30 hours</p>

Module title	Computational Materials Design
Responsibility	Chair for Theoretical Physics VII
Type of course	Lecture (2 SWS) and Exercises (1 SWS)
Desired learning outcomes	Aim of this course is to provide basic competencies on the field of computational materials' design. Students will gain an overview of battery-relevant materials properties and the computational methods for their computation. Finally, students will get a basic introduction into machine learning methods for the prediction of such properties.
Contents	<ul style="list-style-type: none"> • <u>Structural materials' properties:</u> crystal structures, crystal stabilities, elastic constants, crystal vibrations and phonons, thermal properties, thermal expansion, heat conductivity • <u>Electronic materials' properties:</u> density of states, Fermi-Dirac statistics, heat capacity, Bloch theorem, Conductivity • <u>Computational Methods:</u> theoretical background of density functional theory, Hohenberg-Kohn theorems, Kohn-Sham density functional theory, exchange-correlation functionals, local density and generalised gradient approximations, advanced density functional theory • <u>Machine learning:</u> concepts, neural networks and kernel-based approaches advantages and disadvantages of machine learning
Admission requirements	Recommended: alignment module physics or basic physics & quantum mechanics
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	German / English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours Exercises: 15 hours; Preparation and follow-up: 30 hours Exam preparation: 60 hours

Module title	Post Li-ion Battery Technologies
Responsibility	Chair of Inorganic Active Materials for Electrochemical Energy Storage
Type of course	Lecture (2 SWS) and Seminar (1 SWS)
Desired learning outcomes	The objective is to present to the students the array of technologies which are at the research stage and being developed as "post Li-ion", i.e. as improvements beyond the current Li-ion batteries, representing the state of the art. Examples include Na-ion, solid-state-batteries, Zn-based and Li-S batteries, as well as nanostructuring solutions to improve materials properties.
Contents	The course will cover specifically: Na-ion and K-ion batteries; solid-state-batteries (including a detailed discussion on ionic conductivity); multivalent chemistries (Mg, Ca, Al); Zn-based batteries as well (including aqueous), Li-S and Li-air batteries. The course will also cover nanostructuring solutions for advanced electrodes in Li-ion and post-Li-ion batteries.
Admission requirements	Recommended: all alignment modules and Battery Materials I or II
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination (75%) and seminar (25%)
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 30 hours Seminar: 15 hours; Preparation and follow-up: 30 hours Exam preparation: 45 hours

Module title	Solid Inorganic Materials: Nanochemistry
Responsibility	Chair of Inorganic Chemistry I and III
Type of course	Lecture (2 SWS) and Practical training (3 SWS)
Desired learning outcomes	In this course, students acquire a sound overview of current developments in the field of solid inorganic materials with a focus on aspects of nanochemistry.
Contents	<p>The lecture presents properties, applications and fundamental aspects of solid inorganic functional materials. Emphasis is placed on the mechanisms of different synthesis routes as well as on modern analytical strategies. The following points will be covered:</p> <ul style="list-style-type: none"> • Inorganic nanotechnology as well as colloids, pigments, nanorods and nanowires. • Inorganic composites and fillers including biogenic materials such as nacre and bone tissue. • Polymorphism and "crystal engineering" of molecular systems and their influence on active ingredient production • Supramolecular inorganic chemistry and host-guest compounds. • Semicrystalline and amorphous materials such as glasses, glass ceramics, phase transfer materials and photonic crystals <p>In the practical training, students deepen their practical skills by working on a current research project in the relevant working groups under the guidance of an experienced doctoral student.</p>
Admission requirements	None
Availability frequency / Duration	Every Winter semester (WiSe) / 1 semester
Recommended semester	2 nd course semester
Language of instruction	German / English
ECTS credit points	5 LP
Module testing	Written or oral examination (60%) and graded Practical training (40%)
Student work input In hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours Practical training: 45 hours; Preparation and follow-up: 15 hours Exam preparation: 30 hours</p>

Engineering sciences

Module title	Battery-Management-Systems
Responsibility	Junior professorship for Methods for Battery Management
Type of course	Lecture (2 SWS) and Practical training (2 SWS)
Desired learning outcomes	Overview of the essential tasks and components of a battery management system. Knowledge of the methods for monitoring and control of batteries. Ability to apply methods for state estimation and control of battery systems.
Contents	Electrical, physical and mathematical fundamentals of battery systems and their management. Fundamentals of the behavior of battery cells and battery packs in operation; fundamentals of the models and methods used in battery management; application of the methods for state estimation, prediction and control; fundamentals of dealing with measurement uncertainties; fundamentals of model predictive control in battery systems; electrical components of the battery system and hardware and software architecture of battery management systems.
Admission requirements	Advanced study skills; engineering knowledge to the extent of a university Bachelor's degree, especially in mathematics, electrical engineering and control engineering.
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	3 rd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	Written examination (60%) and graded Practical training (40%)
Student work input in hours	Lecture: 30 hours; Preparation and follow-up 30 hours Practical training: 30 hours; Preparation and follow-up: 30 hours Exam preparation: 30 hours

Module title	Electrical Energy Systems
Responsibility	Chair Electrical Energy Systems
Type of course	Lecture (2 SWS), Exercises (1 SWS) and Practical training (1 SWS)
Desired learning outcomes	Expertise and skills in the operation and optimization of energy systems
Contents	<ul style="list-style-type: none"> • Description and modelling of electrical power systems • The control and operation management of power systems • The methods of energy management • Fundamentals of optimization of power systems under the constraints of economy, efficiency, reliability, longevity and security of supply • The methods of optimization include gradient-based and gradient-free methods • Constrained optimization methods and globally optimal methods. • Electric power systems covered from distributed electrochemical storage to power plants, distribution grids, microgrids, and electric transmission systems • Application and deepening of the knowledge by means of exercise examples
Admission requirements	Module Battery System Technology 1
Availability frequency / Duration	Every Summer semester (SoSe) / 1 semester
Recommended semester	2 nd course semester
Language of instruction	German / English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours Exercise: 15 hours; Preparation and follow-up: 30 hours Practical training: 30 hours Exam preparation: 30 hours

Module title	Electrode Design of Electrochemical Energy Storage
Responsibility	Chair of Electrode Design for Electrochemical Energy Systems
Type of course	Lecture (2 SWS) and Exercises (2 SWS)
Desired learning outcomes	<p>At the end of the course, the students will be able to:</p> <ul style="list-style-type: none"> • Compute essential properties relevant to electrode design. • Apply principles of material design to create effective battery electrodes. • Analyse battery cell production equipment, processing flows and methodologies. • Understand the assembly processes for real-world electrode fabrication.
Contents	<p>This course offers a comprehensive examination of the principles that form the foundation for battery electrode design within various battery technologies. It begins with an introduction to the physics of rechargeable batteries, with a special focus on electrochemical cells and their functionality. This part of the course elucidates the thermodynamics of batteries and guides students in calculating key properties pertinent to electrode design, such as gravimetric and volumetric capacities, electromotive force, and maximum energy content. The course then transitions into exploring the dynamics of various processes, followed by a detailed discussion on design principles. Emphasizing the fundamental physical and chemical principles and incorporating modeling techniques, this section provides an understanding of electrode construction. The subsequent modules examine battery cell production equipment, processing flows, and methodologies that are tailored specifically for creating functional electrodes. This provides students with an all-encompassing perspective of real-world electrode fabrication, ensuring a well-rounded and applied understanding of the subject matter.</p>
Admission requirements	Required: Alignment modules A to C.
Availability frequency / Duration	Every Semester / 1 semester
Recommended semester	2 nd course semester
Language of instruction	English
ECTS credit points	5 LP
Module testing	written or oral examination
Student work input in hours	<p>Lecture: 30 hours; Preparation and follow-up: 30 hours</p> <p>Exercises: 30 hours; Preparation and follow-up: 30 hours</p> <p>Exam preparation: 30 hours</p>

Module title	Modelling and Simulation of Electrochemical Energy Storage Systems
Responsibility	Chair of Electrical Energy Systems
Type of course	Lecture (2 SWS) and Practical Training (2 SWS)
Desired learning outcomes	<ul style="list-style-type: none"> • Knowledge of the fundamentals and theories of the processes taking place in an electro-chemical storage systems; • Acquisition of competences in the methods and approaches of modelling and simulation of electrochemical storage devices.
Contents	<ul style="list-style-type: none"> • The theory of the fundamentals of electrochemical storage: electrochemical potential and thermodynamics, mass transport in electrolyte and electrode, double layer and electrode kinetics. • The methods of modelling and simulation of electrochemical storage in theory and practice: modelling concepts, model classes. • Modelling approaches are dealt with for the following topics: concentrated equivalent circuit models, spatially discretised lead models, Newman model for the simplification of porous structures, finite element method for the solution of partial differential equations, thermal modelling, electrochemical impedance models (EIS) with an in-depth look at distributed relaxation times (DRT). • Finally, there is an outlook on further modelling approaches such as Gaussian process models or neural networks as well as a classification and evaluation of the models dealt with.
Admission requirements	Module Battery Systems Technology 1
Availability frequency / Duration	Every winter semester (WiSe) / 1 Semester
Recommended semester	2 nd course semester
Language of instruction	German
ECTS credit points	5 LP
Module testing	Written or oral examination (60%) and graded Practical training (40%)
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 15 hours, Tests during practical training (programming and documentation): 30 hours; Preparation and follow-up of tests: 45 hours Exam preparation: 30 hours

Module title	Solid State Materials Characterization
Responsibility	Chair of Electrochemical Process Engineering
Type of course	Lecture (2 SWS) and Seminar (2 SWS)
Desired learning outcomes	The objective is to acquire core competences in the field of solid-state materials characterization. The students will gain an overview of spectroscopy, microscopy, and diffraction methods commonly used to analyse battery materials ex-situ, in-situ and operando. They will learn about different set-ups, lateral and depth resolution, get to know the working principles and the respective methodical constraints. The students will be able to utilise this new knowledge to select the most promising method or combination of techniques.
Contents	The lecture covers the following topics: overview and classification of characterization techniques, general experimental set-ups, sources, monochromators, detectors. After the general introduction, each further lecture will highlight a specific method, its working principle, advantages and constraints. X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), electron microscopy (SEM, TEM) and other relevant techniques will be covered in depth. This will allow the students to pick the most suited methodical approach for several practical and battery-related examples.
Admission requirements	Recommended: Alignment modules Materials Science and Physical Chemistry.
Availability frequency / Duration	Every Summer semester (SoSe) / 1 Semester
Recommended semester	2 nd course semester
Language of instruction	German
ECTS credit points	5 LP
Module testing	Written examination (66%) and graded presentation (33%)
Student work input in hours	Lecture: 30 hours; Preparation and follow-up: 30 hours Seminar (abstract and guided writing): 30 hours; Preparation and follow-up: 30 hours Exam preparation: 30 hours

Module title	Systems Engineering and Requirements Engineering
Responsibility	Chair of Systems Engineering for Electrochemical Energy Storage
Type of course	Lecture (2 SWS) and Exercise (2 SWS)
Desired learning outcomes	<ul style="list-style-type: none"> • Explain the tasks and objectives of SE and the role of the SE engineer. • Explain phases in the system life cycle and different life cycle models • Identify system interfaces and meaningful system limits • Identify stakeholders and determine requirements for a system • Formulate good natural language requirements specifications themselves and evaluate existing ones • Create simple system models using SysML and understand more complex diagrams • Describe the behaviour and architecture of a system using SysML • Apply methods for solution space expansion • Apply methods and techniques for evaluating solution alternatives
Contents	<p><u>Basics of Systems Engineering (SE):</u> system definition and delimitation, goals and tasks in SE, phases in SE and different life cycle models; importance of good requirements, requirements elicitation, formulation and management; methods and techniques for expanding the solution space; evaluating variants and making decisions;</p> <p><u>model-based SE with SysML:</u> introduction and application of the different diagrams; verification and validation in the system development process.</p>
Admission requirements	none
Availability frequency / Duration	Every semester / 1 semester
Recommended semester	2 nd or 3 rd course semester
Language of instruction	English and German (alternating)
ECTS credit points	5 LP
Module testing	oral examination
Student work input in hours	Lecture: 30 hours; Preparation and follow up: 25 hours Exercises: 30 hours; Preparation and follow up: 15 hours Exam preparation: 50 hours