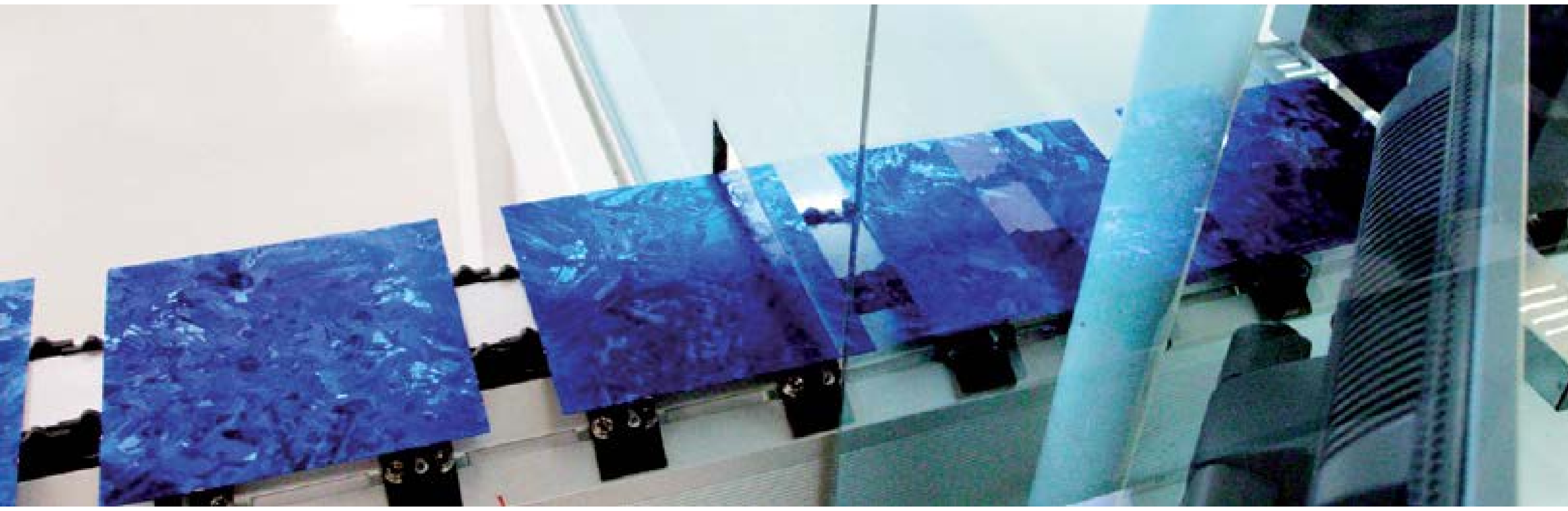
Master

Photovoltaics Engineering Science

Module Manual



Contents

All modules are self-contained and modules of winter and summer semester do not rely on each other (prerequisites only as mentioned at the end of the respective description; modules CSSC and TFSC need module PSC in parallel).

The modules of semester 1 (cf. schedule below) are usually taught in the winter semester, the others in the summer semester.

The program can be started either in the winter or summer semester.

Semester	Credits 1–5	Credits 6–10	Credits 11–15	Credits 16–20	Credits 21–25	Credits 26–30
1.	Physics of the Solar Cell	Crystalline Silicon Solar Cells	Thin Film Solar Cells	Cell and Materials Diagnostics	Solar System Applications	Power Electronics in Photovoltaic Systems
2.	Solar Modules and Components	System and Component Reliability	System Design, Monitoring, Yield and Performance Analysis,	Storage Systems	Electric Grids, Solar Energy Integration	Business Studies
3.	Master Thesis					

	Credits	Share
Modules directly related to photovoltaics engineering	55	61%
Complementary module	5	6%
Master thesis	30	33%
	90	100%

PES/01 Physics of the Solar Cell (PSC) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Norbert Bernhard	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises	30 h
	Computer exercises (computer lab)	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Computer Pool	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain a fundamental physical understanding of the function principle of a solar cell. They shall be able to understand the influence of various physical parameters on the performance of a solar cell. They shall gain a basic understanding of the theoretical formalism on which modern solar cell simulation programs are based on. They shall be able to perform various calculations or estimations analytically or numerically. They should be able to simulate important solar cell functionalities and their dependence on critical parameters on the computer (programs AFORS-HET and PC1D are used).

Contents:

- Fundamentals of the electronic band structure of a semiconductor
- Density of states distribution function and effective density of states at band edges
- Doping in semiconductors, Fermi-Dirac statistics, Boltzmann approximation
- Electron transport in semiconductors, drift and diffusion currents
- Charge carrier mobility and diffusion coefficient
- Electrostatics of the p/n junction (charge density, electric field strength, electric potential)
- The non-illuminated p/n junction in steady state
- Diode equation and IV characteristics
- Charge carrier generation and recombination
- Dielectric function, absorption coefficient, absorption profiles
- Photogeneration of charge carriers, direct and indirect semiconductors
- Recombination mechanisms (radiative, SRH, Auger, surface recombination)
- Fermi level, quasi-Fermi levels, electrochemical potential
- The illuminated p/n junction in steady state
- Semiconductor equations and their solution
- Solar cell equation (diode equation under illumination)
- Diffusion and drift determined charge carrier collection
- Semiconductor heterojunctions and metal-semiconductor junctions
- Heterojunction solar cells and Schottky cells
- Metal-insulator heterojunction (MIS cell)
- Chemical and field-effect surface passivation
- Physical limitations of the conversion efficiency
- Photons and Bose-Einstein statistics; the solar cell as thermodynamic engine
- Theoretical limits of conversion efficiency

Literature:

- Peter Würfel and Uli Würfel: Physics of Solar Cells, 3rd ed., Wiley VCH, Weinheim, 2016
- Jenny Nelson: The Physics of Solar Cells, Imperial College Press, London, 2003
- Gottfried H. Bauer: Photovoltaic Solar Energy Conversion, Springer, Heidelberg et al., 2015
- Thomas Dittrich: Materials Concepts for Solar Cells, 2nd ed., World Scientific, London, 2018

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor´s degree; especially: electrodynamics, thermodynamics, optics, atomic and solid state physics
- Mathematics according to Engineering Science Bachelor´s degree: infinitesimal calculus (differentiation and integration), differential equations, complex numbers

PES/02 Crystalline Silicon Solar Cells (CSSC) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Jörg Bagdahn / Prof. Dr. Norbert Bernhard	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Laboratory experiments (and excursions)	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain a fundamental understanding of the properties and manufacturing processes of the silicon base material and the silicon wafers. They shall acquire an understanding of the structure, types and manufacturing processes of crystalline silicon solar cells. They shall be able to understand the interdependence between process parameters in the production process and performance parameters of the final solar cell.

Contents:

- Silicon production from raw materials; production of poly-crystalline base material
- Crystal growth; role of defects in crystals; doping of base material
- Production of mono- and multi-crystalline wafers
- Wafering (slurry and diamond-wire sawing)
- Saw damage removal and texturing etch (alkaline, acidic, plasma)
- Theory of the emitter diffusion (Fick´s laws, diffusion equation, analytical solutions)
- Diffusion process in the horizontal quartz furnace and the conveyor belt furnace
- Emitter formation by ion implantation
- Gettering; selective emitters
- Removal of phosphorus (PSG) or boron glass (BSG) layer
- Monitoring of the doping density
- Anti-reflective coatings
- Surface passivation (front and rear side), PECVD, ALD
- Metal contacts, screen printing process
- Anneal and firing process
- Back-surface field
- Alternative metallization processes
- Wafer edge isolation
- Passivated emitter and rear cell (PERC), back-side passivation
- n-doped base layer, p-doped emitter (PERT, PERL)
- Interdigitated back-contact cell (IBC)
- Silicon heterojunction (SHJ) cell, passivation by a-Si:H, amorphous/poly-Si contacts
- Tunnelling contacts, TOPcon (POLO) cell and other advanced concepts
- Tandem cell (c-Si plus perovskite)

Literature:

- Konrad Mertens: Photovoltaics: Fundamentals, Technology and Practice; Wiley, 2rd ed., 2019
- Antonio Luque, Steven Hegedus (ed.): Handbook of Photovoltaic Science and Engineering, 2nd ed., Wiley, Chichester, 2011
- Angele Reinders et al. (ed.): Photovoltaic Solar Energy: From Fundamentals to Applications, Wiley, Chichester & Hoboken, 2017
- Original research and review articles (e.g. Proc. EU PVSEC, Progress in Photovoltaics)

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor; module PSC in parallel
- Chemistry (or materials science) knowledge according to Engineering Science Bachelor
- Mathematics according to Engineering Science Bachelor´s degree: infinitesimal calculus (differentiation and integration), differential equations, complex numbers

PES/03 Thin Film Solar Cells (TFSC) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Norbert Bernhard	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Laboratory experiments (and excursions)	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain a fundamental understanding of the various thin film technologies, which are used for manufacturing thin film solar cells. They shall acquire an overview of the various thin film solar cells types and shall be able to recognize similarities and differences between the various cell types.

Contents:

- Fundamentals of vacuum and high-vacuum technology
- Deposition technologies (PVD, CVD, chemical bath deposition)
- Monolithic series connection of solar cells
- Transparent conducting oxides (TCOs), intrinsic and extrinsic doping
- Amorphous silicon and micromorphous silicon solar cells
- Material properties and deposition technology (PECVD)
- Drift determined vs. diffusion determined cell
- Copper indium (gallium) diselenide (sulfide) solar cells (chalcopyrite PV)
- Material properties, heterojunction cell, phase diagram
- Co-evaporation vs. sequential deposition
- Cd-free cells; Kesterites; KF, RbF treatment
- Anderson model of heterojunctions, deviations from Anderson model in reality
- Cadmium telluride solar cells
- Material properties, special deposition technologies (VTD, CSS), $CdCl_2$ post-treatment
- Perovskite solar cells (as single junction cells and as window cell for tandem devices)
- Perspective of the c-Si/perovskite tandem device
- Dye sensitized solar cells (liquid and solid-state electrolyte cells)
- Organic solar cells (small molecules vs. polymers)
- HOMO & LUMO concept of organic devices; exciton charge transport
- Gallium arsenide based solar cells as epitaxial thin-film cells on a crystalline bulk substrate
- Tandem, triple and multiple junction concept for concentrating PV

Literature:

- Konrad Mertens: Photovoltaics: Fundamentals, Technology and Practice; Wiley, 2rd ed.,2019
- Jef Poortmans and Vladimir Arkhipov (ed.): Thin Film Solar Cells: Fabrication, Characterization and Applications, Wiley, Chichester, 2006 (corrected reprint 2007)
- Roland Scheer, Hans-Werner Schock: Chalcogenide Photovoltaics, Wiley-VCH, Weinheim, 2011
- C. Brabec, V. Dyakonow, U. Scherf (ed.): Organic Photovoltaics, Wiley-VCH, Weinheim 2008
- Antonio Luque, Steven Hegedus (ed.): Handbook of Photovoltaic Science and Engineering, 2nd ed., Wiley, Chichester, 2011
- Angele Reinders et al. (ed.): Photovoltaic Solar Energy: From Fundamentals to Applications, Wiley, Chichester & Hoboken, 2017
- Original research and review articles (e.g. Proc. EU PVSEC, Progress in Photovoltaics)

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor; module PSC in parallel
- Chemistry (or materials science) knowledge according to Engineering Science Bachelor

PES/04 Cell and Materials Diagnostics (CMD) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Christian Hagendorf (Fraunhofer CSP)	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Laboratory experiments (and excursions)	15 h
	Self-study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain fundamental knowledge in methodology and analytical techniques for characterization of solar cells and materials of photovoltaic modules. Lectures, exercises and excursions will provide an overview on typical electrical, optical, microstructural and element-analytical methods that are used in industrial defect diagnostics as well as material characterization in research and development. The typical workflow of solar cell loss analysis, defect localization, sample preparation and microstructural root cause analysis will be taught at examples from applied research projects.

Contents:

- Introduction to solar cell and materials diagnostics
- Electrical and optical characterization, advanced spatially resolved methods
- Methodology and workflow in PV-cell and materials defect diagnostics (c-Si-PV, thin film-PV, next generation solar cells)
- PV cell defect diagnostics and non-destructive testing methods (case studies: PID)
- Microstructure diagnostics of materials by SEM, ESEM, TEM, STEM, FIB, AFM… and analytical methods (EDX, WDX, EBSD, EELS, XPS, AES, SIMS…)
- Industrial quality control (sun simulators) and outdoor metrology for advanced functional testing and technology optimization

Literature:

- Antonio Luque (Editor), Handbook of Photovoltaic Science and Engineering, Wiley 2011
- Christiana Honsberg, Stuart Bowden, www.pveducation.org, internet, 2017
- L. Reimer, P. H. Hawkes, Scanning Electron Microscopy, Springer 2010
- H. Kohl, L. Reimer, Transmission Electron Microscopy, Springer, 2008
- P. H. Hawkes, J. C.H. Spence, Science of Microscopy, Springer, 2007
- H. Bethge, J. Heydenreich, Electron Microscopy in Solid State Physics, Elsevier, 1987

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor´s degree; especially: electrodynamics, thermodynamics, optics, atomic and solid state physics
- Mathematics according to Engineering Science Bachelor´s degree: infinitesimal calculus (differentiation and integration), differential equations, complex numbers

PES/05 Solar System Applications (SSA) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Carlos Meza	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminars)	30 h
	Laboratory experiments (and excursions)	15 h
	Self-study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

This course aims to provide students with a broad understanding of the current and future applications of photovoltaic systems (PVS). The module is intended to give an application-related bird´s eye view on system technology, complementary to the other rather specifically physical, chemical or materials science and power electronics-related subjects of the winter semester. After the completion of this module, the students should be able to understand why PV systems are useful in different applications. Students will develop skills to identify the advantages and disadvantages of different solar system applications and assess their economic value. This module is aimed to generate a comprehensive, but not too technical, understanding of PV system technology, given that PV systems technical details are covered in other modules of the Master Program.

Contents:

- Main elements of a photovoltaic system: Photovoltaic cells and modules; Power electronic converters; Batteries.
- Variables and conditions that affect the performance of a PV system: Solar irradiance and inclined structures, vertical mounting structures and trackers (single- and dual-axis); Temperature; Contingencies (lightning, over-voltage and current) and protection devices.
- Power load characterization to understand the applicability of a PV system: Power demand vs. energy demand; Consideration for AC loads; Pumps and other inductive loads.
- Solar system application according to the load: Grid-connected systems; Stand-alone connected systems.
- Solar system application according to the context and end use: Floating PV (FPV); Agrivoltaics (APV); Building integrated photovoltaic (BIPV); Vehicle integrated photovoltaic (VIPV); Photovoltaic embedded in small electronic devices: Other novel applications.
- Techno-economic assessment of solar system applications.

Literature:

- Louie, Henry. Off-grid electrical systems in developing countries. Cham, Switzerland: Springer International Publishing, 2018.
- Rekioua, Djamila, and Ernest Matagne. Optimization of photovoltaic power systems: modelization, simulation and control. Springer Science & Business Media, 2012.
- Deutsche Gesellschaft für Sonnenenergie (DGS). Planning and installing photovoltaic systems: a guide for installers, architects, and engineers. Routledge, 2013.
- Articles from IEEE Xplore, Science Direct and MDPI databases.

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor´s degree; especially optical properties of the material, energy band models etc.
- Fundamentals of electrical engineering: electronic devices (diode, transistor, capacitance etc.), DC circuits, series and parallel connection of devices, AC circuits (1 phase, 3 phases)

PES/06 Solar Modules and Components (SMC)		
		Compulsory module
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Norbert Bernhard	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Computer exercises	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain a fundamental understanding of the structure and function of a solar module. They shall be able to understand the main differences between crystalline Si and thin film modules. They shall understand the series and parallel connection of solar cells to a module. They shall understand how a bypass diode can protect the module in case of partial shading and recover at least a part of the electric energy production. They shall understand the components of a modules and their role in the modules.

Contents:

- Structure of crystalline silicon solar modules
- Structure of thin film solar modules
- Nominal and performance parameters of solar modules, data sheets
- Dependence of module parameters on irradiance and temperature
- Series and parallel connection of identical solar cells
- Series and parallel connection of non-identical solar cells
- The current-voltage characteristics of a module in all quadrants
- Reverse bias and reverse current regime
- Thermal breakdown under reverse bias
- Shading impact on solar module performance
- Bypass diodes and their role in protecting cells and modules and recovering losses
- Overview of manufacturing process of solar modules
- Solar glass (properties and manufacturing)
- Encapsulation of solar modules (polymers and processes)
- Back-sheets for solar modules
- Double-glass modules
- Joining technologies (soldering, welding, glueing)
- Advanced module concepts (half-cell, shingled, bifacial)
- Cell-to-module efficiency
- Perspectives of future developments

Literature:

- Konrad Mertens: Photovoltaics: Fundamentals, Technology and Practice; Wiley, 2nd ed., 2019
- Heinrich Häberlin: Photovoltaics, System Design and Practice, Wiley 2012
- Harry Wirth, Karl-Anders Weiß, Cornelia Wiesmeier: Photovoltaic Modules: Technology and Reliability, De Gruyter, 2016
- Original research and review articles (e.g. Proc. EU PVSEC, Progress in Photovoltaics)

Prerequisites:

- Fundamentals of electrical engineering: DC circuits, series and parallel connection of devices, ideal and linear current source, diode equation, bipolar and Schottky diodes
- Fundamentals of chemistry or materials science: inorganic chemistry, organic chemistry (especially polymers), phase diagrams

PES/07 System Design, Monitoring, Yield and Performance Analysis, Markets (SMYM)	**Compulsory module**	
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Norbert Bernhard (responsible); Dipl.-Ing. (FH) Sebastian Dittmann (PVsyst)	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Computer exercises	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Computer Pool	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall gain a fundamental understanding of the system design, monitoring, yield and performance analysis of a solar system. They should be able to perform a planning of solar system and calculate the energy yield forecast by using a commercial solar system planning software (program PVsyst is used). They shall acquire a basic understanding how the PV market works.

Contents:

- Solar irradiance (direct, diffuse, albedo)
- Geographic distribution of irradiance
- Models for estimation of diffuse portion
- Dependence of direct, diffuse and albedo irradiance on module inclination
- Radiation monitoring (pyranometers, reference cells)
- Shading analysis
- Different system concepts (string inverter, central inverter, master-slave, module inverter)
- Series and parallel connections of modules
- Reverse current regime, string diodes, string fuses
- Generator junction box, circuit breakers, surge arresters
- Solar cable sizing
- Power and voltage sizing of the inverter; inverter data sheets
- System monitoring, normalized yields and losses
- Performance analysis
- Yield forecast
- Elementary economic considerations
- Solar system planning software (PVsyst)
- Market development in the past, scenarios for the future

Literature:

- Konrad Mertens: Photovoltaics: Fundamentals, Technology and Practice; Wiley, 2nd ed. 2019
- Heinrich Häberlin: Photovoltaics, System Design and Practice, Wiley 2012
- Deutsche Gesellschaft für Sonnenenergie (DGS; Ed.): Planning and Installing Photovoltaic Systems, 3rd ed., 2013, Routledge
- Nicala Pearsall (ed.): The Performance of Photovoltaic Systems: Modelling, Measurement and Assessment, Woodhead Publishing, Cambridge (MA) & Kidlington, 2017
- Original research and review articles (e.g. Proc. EU PVSEC, Progress in Photovoltaics)

Prerequisites:

- Fundamentals of electrical engineering: DC circuits, series and parallel connection of devices, AC circuits (1 phase, 3 phases)

PES/08 System and Component Reliability (SCR) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Dr. Bengt Jäckel (responsible), in cooperation with Prof. Dr. Jörg Bagdahn, Dipl.-Ing.(FH) Sebastian Dittmann, and lecturers from the Fraunhofer Center for Silicon Photovoltaics (CSP)	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar or project work)	30 h
	Laboratory experiments (and excursions)	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments, Seminar	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Seminar (~30min presentation) with questions from Lecturer and audience plus written paper about the seminar topic	

Target skills:

The students shall gain a fundamental understanding of impact parameters for the reliability of PV modules, systems, and components. They shall understand the physical mechanisms of failure processes and test procedure how to monitor degradation processes. Furthermore, a fundamental understanding of accelerated test procedures to forecast the expected lifetime of solar cells and modules shall be obtained.

Contents:

Block #0:

- General introduction to PV module reliability and its necessity

Block #1: Introductions to PV failure modes

- Overview of PV System and Component reliability
- Introduction to mechanical failures of solar cells and modules
- Reliability and failure modes of solar cells, modules and systems
- Related terms and definitions
- Introduction to “mission profiles” of PV modules
- Materials: mechanical properties and failure modes (elasticity, plasticity, fatigue, failure with focus on e. g. solder joints and ribbons)
- Thermo-mechanical fatigue interconnections

Block #2:

- Standardization: On local, European, and international level
- IEC standards for module reliability and PV module testing
- Optical properties and characterization of solar modules
- Electrical characterization of solar modules
- Outdoor testing of solar modules

Block #3

- Module related failures and loss mechanisms
    - LID kind of effects
    - Cell cracks and snail trails
    - Potential induced degradation (PID)
    - Soiling

Block #4

- New PV Applications and their challenges for Reliable operation: Building integrated photovoltaics (BIPV); Agri-PV, Floating PV

Literature:

- Konrad Mertens: Photovoltaics: Fundamentals, Technology and Practice; Wiley, 2014
- Karl-Anders Weiß: Photovoltaic Modules - Reliability and Sustainability, De Gruyter 2021

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor´s degree; especially mechanics, thermodynamics
- Fundamentals of Photovoltaics, electrical engineering and materials science
- Fundamentals of chemistry or materials science: inorganic chemistry, metals, glass, organic chemistry (especially polymers)

PES/09 Storage Systems (SS) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Carlos Meza	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminars)	30 h
	Laboratory experiments (and excursions)	15 h
	Self-study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

Energy storage is fundamental to massively incorporating photovoltaics into modern energy systems. In this module, students should be enabled to understand the working principles, benefits, and limitations of existing energy-storing systems. This module also allows students to understand how storage can provide flexibility to grid-connected PV generation. Students will also learn how to size and select storage systems for grid-connected and off-grid systems. In this module, students will use modeling and simulation strategies to understand the power behavior of PV plants and storage systems.

Contents:

- Power flow modeling of storage units.
- Types of storage technology
  - Electrochemical (e.g., lead-acid, lithium-ion)
  - Mechanical (e.g., flywheel, compressed air, pumped hydro)
  - Thermal (e.g., molten salts)
  - Electrical and magnetic (e.g., supercapacitors, magnetic energy storage)
  - Hydrogen based.
- Storage units in stand-alone PV systems: sizing, selection criteria, modeling, and simulation.
- Storage units in grid-connected PV systems: curtailment avoidance, peak-shaving, sizing, selection criteria, modeling, and simulation.

Literature:

- Huggins, R.A. Energy Storage, Springer, 2nd ed., Heidelberg 2016
- Louie, Henry. Off-grid electrical systems in developing countries. Cham, Switzerland: Springer International Publishing, 2018.
- Breeze, Paul. Power system energy storage technologies. Academic Press, 2018.
- Articles from IEEE Xplore, Science Direct, and MDPI databases.

Prerequisites:

- Physics knowledge according to Engineering Science Bachelor´s degree, especially basic terms of energy engineering.
- Fundamentals of electrical engineering,

PES/10 Electric Grids and Solar Energy Integration (EGSI) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Ralph Gottschalg	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises (or seminar)	30 h
	Laboratory experiments (and excursions)	15 h
	Self study	75 h
Forms of Media	Moodle, online courses, presentations, computing simulations, laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students will be able to successfully integrate a PV system into a power network. They will gain a fundamental understanding of the structure and working principles of electric grids. They shall understand the special requirements of grid services to be provided by PV power plants and the challenges, but also the chances, related to it. The students shall understand the paradigm changes related to grid contol, if in the medium-term future the grid might be dominated by volatile renewable energy sources or in the long-term future even consist only of renewable sources. The special challenges to integrate volatile energy sources into the grid in larger and larger quantities will be taught and the key performance indicators of such installations will be discussed. A small power system will be simulated to gain an understanding of the issues involved in the integration of PV into the power system from the perspective of both, the network operator as well as the PV system integrator. The feasibility of an all renewable power system is being discussed.

Contents:

- Managing demand and supply
- Voltage levels of electric grids (high-voltage, medium-voltage, low-voltage) and interfaces
- Connection of PV power plants to the electric grid (to medium-voltage or low-voltage grid)
- Actual and emerging standards for grid connection of PV inverters
- Centralized vs. decentralized public grid design
- Controllable local transformers for low-voltage grid stabilization at high PV integration levels
- PV grid integration complementary with other renewable or non-renewable energy forms
- Smart grids vs. classical grid control
- Future challenges and developments
- Security of supply issues
- Sustainable energy systems

Literature:

- Vincent J. Winstead: Electric Power Systems: Electrical Grid Fundamentals and Sustainable Power Integration, Taylor and Francis, publication date March 2018 announced
- Heinrich Häberlin: Photovoltaics, System Design and Practice, Wiley 2012
- Original articles

Prerequisites:

- Fundamentals of electrical engineering: DC circuits, AC circuits (1 phase, 3 phases), impedances and admittances, active and reactive power in an AC circuit, transformers, fundamentals of power electronics

PES/11 Power Electronics in Photovoltaic Systems (PEPS)		**Compulsory module**
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Carlos Meza	
Semester	1. or 2.	
Workload	150 hours, including 75 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises	30 h
	Laboratory experiments (and excursions)	15 h
	Self study	75 h
Forms of Media	Blackboard, Transparencies, Presentations, Laboratory experiments	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (2 h) or oral examination (30 min)	

Target skills:

The students shall get a fundamental understanding of the basics of power electronics, which is the basis of inverters and DC/DC-converters in PV systems. They shall be able to understand the working principles of the basic power electronic devices (MOSFETs, IGBTs, thyristors) and how these devices are used in circuitry to establish inverters and converters. They shall be able to simulate and to design power electronic circuits for various applications with mathematical models. They shall understand
different inverter concepts used in grid-connected or stand-alone systems, and also electronic components and concepts for yield optimization of PV systems, e.g. optimizers for shading situations.

Contents:

- Semiconductor devices for power electronics
- Basic circuitry for converters (AC/DC, DC/DC, DC/AC)
- Inverter concepts (grid-connected, stand-alone, hybrid, module inverters)
- Maximum power point tracking
- Methods of power optimization (power optimizers)
- Electronic loads for module characterization (indoor/outdoor)
- Measurement concepts for current-voltage characteristics recording
- Simulation and control of power converters and inverters
- Battery charge control
- Electric grid services

Literature:

- Erickson, R. W., & Maksimovic, D. Fundamentals of power electronics. Springer Science & Business Media, 2007.
- Zhong, Q. C., & Hornik, T. Control of power inverters in renewable energy and smart grid integration (Vol. 97). John Wiley & Sons, 2012
- Ortega, Romeo, Julio Antonio Loría Perez, Per Johan Nicklasson, and Hebertt J. Sira-Ramirez. Passivity-based control of Euler-Lagrange systems: mechanical, electrical and electromechanical applications. Springer Science & Business Media, 2013.
- Rashid, Muhammad H., ed. Power electronics handbook. Butterworth-Heinemann, 2017.

Prerequisites:

- Fundamentals of electrical engineering: DC circuits, AC circuits (1 phase, 3 phases), impedances and admittances, active and reactive power in an AC circuit, transformers, fundamentals of semiconductor devices and power electronics
- Mathematics: calculation with complex numbers; infinitesimal calculus (differentiation and integration)
- Physics: solid state physics, semiconductor physics

PES/12 Business Studies (BS)

Compulsory module

Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	Prof. Dr. Carsten Fussan	
Semester	1. or 2.	
Workload	150 hours, including 60 teaching hours	
Forms of tuition	Lecture	30 h
	Exercises	30 h
	Self study	90 h
Forms of Media	Blackboard, Transparencies, Presentations	
Awarded Credit	5 Credit Points	
Language	English	
Examination	Written examination (1 h) + Case Study / Presentation (20 min)	

Target skills:
The module provides an introductory overview of the dominant segments of Business Administration. The students get to know the different functional areas and the basic methodology of the science. On this basis, students generate transfers for the design and management of companies especially in the photovoltaic industry. The students are able to design different measures for managing technology driven companies and they can identify related critical success factors. The students understand the logic of modern management and business model oriented thinking. An additional focus of the course is on the introduction to the methods of scientific work based on scientific theoretical principles. Across all topics, the students are to be sensitized for ethical challenges in the company.

Contents:

THE CONTEMPORARY BUSINESS WORLD
- Understanding Business Ethics and Social Responsibility
- Entrepreneurship, New Ventures, and Business Ownership
- Understanding the Global Context of Business

MANAGING THE BUSINESS
- Organizing the Business
- Operations Management and Quality

PEOPLE IN ORGANIZATIONS
- Employee Behavior and Motivation
- Leadership and Decision Making
- Human Resource Management and Labor Relations

PRINCIPLES OF MARKETING: BUILDING RELATIONSHIPS WITH CUSTOMERS FOR COMPETITIVE ADVANTAGE
- Marketing Processes and Consumer Behavior
- Developing and Pricing Products
- Distributing and Promoting Products

MANAGING INFORMATION FOR BETTER BUSINESS DECISIONS
- Information Technology (IT) for Business

THE FINANCIAL SYSTEM AND ISSUES IN FINANCIAL MANAGEMENT
- Business Finances

Literature:

- Ebert, R.; Griffin, R. (newest edition): Business Essentials, Pearson Education
- Robbins, S.; Coulter, M. (2017): Management, Pearson Education
- Daft, R.; Marcic, D. (2018): Understanding Management, Cengage Learning
- Needle, D. (2015): Business in Context. An Introduction into Business and its Environment, Cengage Learning
- Kotler, P.; Armstrong, G. (newest edition): Principles of Marketing, Pearson
- Daft, R.; Murphy, J.; Willmot, H. (2017): Organization Theory and Design: An international Perspective, Cengage Learning

Prerequisites:
Knowledge of the English language

PES/13 Master Thesis (Including Colloquium) **Compulsory module**		
Program	Photovoltaics Engineering Science (Master of Science)	
Lecturer	depending on specific topic	
Semester	3.	
Workload	900 hours	
Forms of tuition	Master thesis	750 h
	Colloquium	150 h
Awarded Credit	30 Credit Points	
Language	English	
Examination	Written thesis and oral presentation (30 min plus 60 min discussion)	

Target skills:

The students shall be able to use and show the ability to transfer basic theoretical knowledge to specific scientific questions.

They shall be able to solve a scientific problem by using scientific methodology.

They shall be able to present their results in a written thesis according to scientific writing and publication standards.

Contents:

Depending on chosen specific topic

Literature:

Depending on chosen specific topic

Prerequisites:
all compulsory modules of 1. and 2.semester