EU CORE

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PROGRAMME SYLLABUS

ERASMUS MUNDUS JOINT MASTER

EU-CORE

European Master on Control of Renewable Energy Systems

CENTRALE NANTES

UNIVERSITY OF ZAGREB

BRANDENBURGISCHE TECHNISCHE UNIVERSITÄT
COTTBUS - SENFTENBERG

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First semester at Centrale Nantes (ECN), France

Courses	Professors	ECTS
Energy transition	Emmanuel ROZIÈRE	4
Wind Energy Basics 1	Sandrine AUBRUN, Caroline BRAUD, Boris CONAN, Vincent LEROY, Laurent STAINIER	4
Wind Energy Basics 2	Sandrine AUBRUN, Caroline BRAUD, Boris CONAN, Vincent LEROY, Laurent STAINIER	4
Power Conversion	Mohamed Assaad HAMIDA	4
Linear Control Systems	Guy LEBRET	4
Nonlinear Control Systems	Franck PLESTAN	4
Wind power project	Mohamed Assaad HAMIDA	4
French language and culture	S. ERTL	2

Second semester at University of Zagreb (UNIZG), Croatia

Courses	Professors	ECTS
Control and Grid Integration Techniques for Renewable Energy Sources	Igor KUZLE, Mario VAŠAK, Ninoslav HOLIEVAC, Matiaj ZIDAR	5
Predictive Control	Mato BAOTIĆ, Branimimr NOVOSELNIK	5
Estimation Theory	Ivan PETROVIĆ, Mario VAŠAK, Ivan MARKOVIC, Nikola HURE	5
Optimal Sizing and Operation of a Photovoltaic System with Storage	Mario VAŠAK, Vinko LEŠIĆ	5
Energy-efficient Buildings Control	Mario VAŠAK, Anita BANJAC, Nikola HURE	5
Project on Control, Estimation and Optimization in Solar Energy	All lecturers	3
Croatian Language and Culture	D. Matovac, R. Đurđević	2

Third semester at Brandenburg University of Technology Cottbus – Senftenberg (BTU), Germany

Courses	Professors	ECTS
Geothermal Energy	Mario RAGWITZ	6
Hydrogen and Fuel Cells	Lars RÖNTZSCH	6
Chemical and Thermal Energy Storage	Fabian MAUß	6
Control of Power-to-X, Storage and X-to-Power Systems	Johannes SCHIFFER	6

Syllabus of courses offered at École Centrale de Nantes

Course 1 – Energy Transition		
Credits: 4	**Fall Semester**	**Compulsory: Yes**
Lectures: 12h	**Tutorials:** 14h	**Labs:** 4h
Responsible: Emmanuel ROZIÈRE		
Professor: Emmanuel ROZIÈRE		

Objectives: At the end of the course, students will be able to:

- Understand and master the major energy, climate and environmental issues of this century
- Master the fundamental concepts and the major orders of magnitude
- Perform "back of an envelope" calculations to quickly analyse a solution while developing a sharp critical sense

Content:

- Climate:
  - Models
  - Greenhouse effect
  - Radiative Forcing
  - Carbon and methane cycles
  - Net zero trajectories
- Energy and economy:
  - Energy now and then
  - Progress
  - Fossil fuels
  - GDP and energy
  - Resources
  - Carbon Tax and emission rights
  - Wright law, learning curve
  - Renewable Revolution
- Environment:
  - Biodiversity loss
  - Impact of energy sources
  - Agriculture
  - Deforestation
- Solutions:
  - Obstacles: game theory
  - Kaya equation and it's limits
  - 8 pillars of transition (consumption control, electrification, decarbonised electricity, synthetic fuels, non-combustion emissions, CO2 capture and storage, adaptation, geo-engineering)
  - Sustainable development
  - The role of engineers and innovation

Recommended texts and further readings:

- P. Hawken, Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming, Penguin, 2017
- H. Ritchie, Not the End of the World: How We Can Be the First Generation to Build a Sustainable Planet, Little, Brown Spark, 2024
- B. Gates, How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need, Penguin, 2021
- V. Smil, Energy and Civilization: A History. The MIT Press, 2017.

- S. Pinker, Le Triomphe des lumières. Les Arènes, 2018
- Y.N. Harari, Sapiens: Une brève histoire de l'humanité. Albin Michel, 2015.
- ''BP Statistical Review of World Energy 2019'', 2019.
- IPCC, "Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Quin, G-K Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]," Cambridge, United Kingdom and New York, NY, USA, 2013.
- C.C. Mann, The Wizard and the Prophet: Science and the Future of Our Planet. Picador, 2019.
- S. Goldstein-Rose, The 100% solution: A Plan for Solving Climate Change. Melville House, 2020.

Keywords: Climate change, green economy, fossil fuels, biodiversity, human progress, energy transition

Course 2 & 3 – Wind Energy basics 1 and 2

Credits: 8	Fall Semester	Compulsory: Yes/No
Lectures: 32h	**Tutorials:** 10h	**Labs:** 4h

Responsible: Sandrine AUBRUN

Professors: Sandrine AUBRUN, Caroline BRAUD, Boris CONAN, Vincent LEROY, Laurent Stainier

Objectives: The aim of the course is to give the basics on the fluid mechanical aspects of a wind turbine operation that is needed to address, in an expert way, a problem of wind turbine or wind farm control.

After drawing the overall panorama of the current wind energy capacity worldwide and in Europe, the general operating principles of a wind turbine and its components are described.

Then, the course addresses all the fluid mechanical aspects of the system: the driving source of energy, i.e. the wind, the wind resource assessment and the power production, the air foil and rotor aerodynamics, the wake effects, the dynamics and vibrations of the structural components, the aero-mechanical couplings and the additional complexities led by floating wind turbine concepts.

Content:

- Key wind energy figures, potential and installed wind power capacity worldwide and in Europe, major development challenges
- Standard wind turbine components and general operating principles (rotor, transmission chain, generator, structures and foundations)
- Basics of meteorology and the atmospheric boundary layer: global meteorological mechanisms, characteristics and physics of the atmospheric boundary layer, wind resources
- Power production and park effects
- Aerodynamics of air foils, theories and models
- Rotor aerodynamics, theories and models
- Basics of structural mechanics: beam theory, numerical finite element models
- Structural dynamics and vibrations: natural modes and frequencies, modal analysis, particularities of rotating systems

- Introduction to aeromechanical couplings: notions of divergence and flutter illustrated on the simplified model of the typical section, equations of the coupled system and methods of resolution
- Introduction to the additional multi-physics aspects for floating wind turbines

Numerical tutorials accompany this programme to learn how to estimate wind turbine output, estimate wind farm effect losses, study the performances and aerodynamic loards acting on a horizontal axis wind turbine, learn how to design a horizontal-axis wind turbine by using open-access multi-physics simulation tools as OpenFast or Qblade.

Abilities: After completing this course the studnets will be able to:

- Understand the current deployment of onshore and offshore wind power, and the challenges of future deployment
- Gain a good understanding of how wind turbines work
- Acquire a basic understanding of atmospheric physics, so as to be able to understand and estimate the specific characteristics of wind farms
- Estimate wind turbine performance and park effects
- Understand and use aerodynamics models for airfoils and rotors
- Understand the mechanical issues involved in the design and operation of wind turbines
- Acquire the basics of structural dynamics, with particular emphasis on slender structures such as wind turbines (with horizontal axes)
- Use a multi-physics simulation tool of wind turbine as OpenFast and Qblade

Recommended texts: The notes of the course will be given by the lecturer.

Further readings:

- Introduction to wind energy systems 2013, Springer-Verlag Berlin and Heidelberg GmbH & Co. K
- Wind Energy Handbook, 2001 John Wiley & Sons, Ltd
- Wind energy explained, - Theory, Design and Application. 2009 John Wiley & Sons, Ltd
- Wind resource assessment - A practical guide to developing a wind project. 2012 John Wiley & Sons, Ltd
- Advances in Wind Turbine Blade Design and Materials, 2013, Woodhead Publishing
- A Modern Course in Aerolasticity, 2022 (6th edition), Springer.

Keywords: Wind energy, capacity statistics and trends, atmospheric boundary layer, wind resource assessment, rotor aerodynamics, wind turbine performance, wake effects, farm effects, structural dynamics, aero-elasticity, fluid-structure interaction

Course 4 – Power Conversion		
Credits: 4	**Fall Semester**	**Compulsory: Yes**
Lectures: 16h	**Tutorials:** 6h	**Labs:** 8h
Responsible: Mohamed Assaad HAMIDA		
Professors: Mohamed Assaad HAMIDA, Mickaël HILARET		

Objectives: This course covers the analysis and synthesis of the main structures in the energy conversion chain. For the sources section, the aim is to present a broad overview of the various conventional and renewable energy sources. For static converters, the aim is to understand the operation and analyse the waveforms of converters such as three-phase rectifiers, choppers and inverters. For electrical machines, the aim is to master the principle of electromagnetic conversion and to model synchronous and asynchronous machines in steady state.

At the end of the course, students will be able to:

- Understand the operation of different renewable energy sources.
- Understand the operation of different types of static converters and their uses in renewable energy systems.
- Know the modelling and simulation of the different components of electrical conversion chain.

Content:

- Renewable energy sources (physical principle, modelling and control objectives)
  - Wind turbine (fixed bottom and floating)
  - Solar panels
  - Hydrogen energy
  - Geothermal energy
- Electric actuators
- Energy storage systems
  - Lithium battery
  - Super-capacitor
  - Fuel-cells
- Power converters
  - Rectifiers
  - Chopper
  - Inverter

Recommended texts: The notes of the course will be given by the lecturers

Further readings:

- CHAKRABORTY, Sudipta, SIMÕES, Marcelo G., et KRAMER, William E. Power electronics for renewable and distributed energy systems. *A Sourcebook of Topologies, Control and Integration*, 2013.
- MUELLER, Markus et POLINDER, Henk (ed.). Electrical drives for direct drive renewable energy systems. 2013.

Keywords: Energy production, Energy storage, Power electronics, Electric machines

Course 5 – Linear Control Systems		
Credits: 4	**Fall Semester**	**Compulsory: Yes**
Lectures: 20h	**Tutorials:** 6h	**Labs:** 4h
Responsible: Guy LEBRET		
Professor: Guy LEBRET		

Objectives: To come back on the basis of classical control for linear systems and give a control methodology starting from the open loop analysis of the system to be controlled to the synthesis of a closed loop using

classical PID type controllers (one degree of freedom controllers) which can be combined with a feed forward part (two degrees of freedom controllers)
Content: • Description of SISO linear systems through the transfer function • Analysis of behaviour (poles/zeros, first/second/more general systems, time domain/frequency domain responses…) • Definition the Control objectives (stability/performances, tracking/regulation) • Nominal/robust performances and the unavoidable trades off between stability and performances • Synthesis of PID type controllers, using frequency approach tunings, in a classical closed loop (one degree of freedom controller strategy) • Possibility to introduction of a feedforward contribution which tries to realize “the inversion” of the first obtained closed loop (two degrees of freedom controllers)
Recommended texts: The notes of the course will be given by the lecturer. **Further readings:** • “Modern Control Systems”, R.C. Dorf and R.H. Biqshop, Prentice Hall, 2011. • “Control Systems Engineering”, N.S. Nise John Wiley & Sons, 2011 • “Control system design”, G.C. Goodwin, S.F. Graebe and M.E. Saldago, Prentice Hall, 2001. • “Mutivariable Feedback Control Analysis and Design”, D.S. Skogestad and I. Postlethwaite, Wiley, 2005
Keywords: Classical control, SISO Linear Systems, two degree of freedom controllers, PID, lead lag controllers
Links with other courses: Nonlinear Control Systems

Course 6 – Nonlinear Control Systems		
Credits: 4	**Fall Semester**	**Compulsory: Yes/No**
Lectures: 16h	**Tutorials:** 4h	**Labs:** 12h
Responsible: Franck PLESTAN		
Professor: Franck PLESTAN		
Objectives: The goal of this course is to give the basis of modern nonlinear control theory. Structural analysis (accessibility, observability) and control/estimation of nonlinear systems are considered. Many examples taken on renewable energy and power systems demonstrate the feasibility of the methodologies. After completing this course, the students will be able to: • Understand the theoretical foundations on the control of nonlinear systems, • Apply advanced nonlinear control on a variety of systems		
Content: • Introduction to the algebraic approach for nonlinear systems and its mathematical tools. • Structural analysis: concepts of relative degree, of controllability and accessibility		

• Control, feedback linearization, decoupling, reference trajectory tracking, adaptive sliding mode control, backstepping • Observation, high gain observer, differentiation • Practical work based on wind energy systems
Recommended texts and further readings: • G. Conte, et al., Algebraic Methods for Nonlinear Control Systems. Theory and Applications, Springer, 2006. • A. Isidori, Nonlinear Control Systems. 2nd edition, Springer, 1989. • Y. Shtessel et al., Sliding Mode Control and Observation, Birkhauser, 2014. • H. Khalil, Nonlinear systems – 2nd edition, Prentice Hall, 1996.
Keywords: Nonlinear systems, controllability, accessibility, linearization, sliding mode, backstepping
Links with other courses: Linear Control

Syllabus of courses offered at the University of Zagreb

<table>
<tr><th colspan="3">Course 1 — Control and Grid Integration Techniques for Renewable Energy Sources</th></tr>
<tr><td>Credits: 5</td><td>Summer Semester</td><td>Compulsory: Yes</td></tr>
<tr><td>Lectures: 30h</td><td>Tutorials: 15h</td><td>Labs: 12 h</td></tr>
<tr><td colspan="3">Responsible : Igor KUZLE, Mario VAŠAK,</td></tr>
<tr><td colspan="3">Professors: Igor KUZLE, Mario VAŠAK, Ninoslav HOLJEVAC, Matija ZIDAR</td></tr>
<tr><td colspan="3">Objectives: Renewable energy sources are the main pillar of low-carbon energy systems of the future. However, their intermittence represents a disturbance on energy grids that needs to be counteracted with proper regulations and control. It also leads to often significant changes of operating regimes of renewable energy plants which is challenging for their control. The course sheds light on these key aspects and puts focus on wind and solar energy as the most exploited forms of renewable energy today. The objectives are as follows:
Understand capacities for integration of renewable energy sources in electricity grids and their specifics.
Get to know technical conditions for integration related to voltage and frequency, as well as fault-ride-through requirements.
Understand the connection of individual wind turbines in a wind farm to the grid and grid conditions for wind farm connection.
Understand the set-up and model of the inverter that enables the connection to the grid of a renewable energy source with internal direct current circuit.
Adopt a classical vector control of the inverter, as well as the inverter output power control – active and reactive, and their interplay.
Adopt the models of photovoltaic cells, modules and arrays.
Know the basic structure of a photovoltaic plant.
Understand control algorithms for the photovoltaic array maximum power point tracking.
Adopt the full-scale grid inverter control for photovoltaic systems.
Learn types of generators used in wind turbines, their corresponding generator converter control and the connection with grid-side inverter, including chopper brake.
</td></tr>
<tr><td colspan="3">Content:
RES integration capacity, RES generation specifics
Technical requirements regarding frequency and voltage, Fault ride-through requirements
Additional RES integration costs. Technical and economical impacts of wind power plants on power system
Electrical wind turbines connection in a wind farm. Grid codes. Wind farm integration into the electrical energy system
Grid-side converter modelling and representation in the rotating dq coordinate system
</td></tr>
</table>

- Grid-side converter control system, including DC-link voltage control and phase-locked loop with its internal control circuit
- Photovoltaic cell, module and array with related models. Solar resource: optimal positioning of the photovoltaic surface
- Control algorithms for maximum power point tracking in photovoltaic systems. Necessary controls for a complete photovoltaic system connected to the grid
- Rehearsal of the turbine-side control for wind turbines. Connection of turbine-side control to generator-side power converter control.
- Generator types in wind turbines and related power converters configuration. Generator to grid connection via AC/DC/AC power converter –basic components and their control for safe and efficient operation

Abilities: After completing this course the students will be able to:

- Explain capacities for integration of renewable energy sources in electricity grids and their specifics
- Explain the connection of individual wind turbines in a wind farm to the grid and grid conditions for wind farm connection
- Explain the set-up and model of the inverter that enables the connection to the grid of a renewable energy source plant with internal direct current circuit
- Use vector control and phase-locked loop for grid-tied inverter control in a plant with a renewable energy source
- Outline the current-voltage model of a photovoltaic array and its grid inverter control for maximum power point tracking
- Explain the fit of wind turbine speed control to generator and grid-side inverters.

Recommended texts: The notes of the course will be given by the lecturers.

Further readings:

- *"Grid Converters for Photovoltaic and Wind Power Systems*", R. Teodorescu and M. Liserre, John Wiley & Sons, 2011.

Keywords: RES grid integration, Voltage and frequency requirements, Grid-side inverter control, Generator-side inverter control, Photovoltaic power plant control, Wind turbine power converters control

Links with other courses: Builds on wind power 1/2 and power conversion from semester 1, uses basic control theory from semester 1 (linear and nonlinear control systems)

Course 2 — Predictive Control		
Credits: 5	Summer Semester	Compulsory: Yes
Lectures: 45h	**Tutorial:** 0h	**Lab:** 8h
Responsible: Mato BAOTIĆ, Branimir NOVOSELNIK		
Professors: Mato BAOTIĆ, Branimir NOVOSELNIK		

Objectives: Predictive control uses predictions of the controlled system evolution to decide on control actions that should be applied. Its applications are steadily rising especially for complex systems under constraints which are often incurred in renewables-based energy systems. It is based on mathematical optimization which requires a significant computational effort and specific implementations. The objectives are as follows: • Understand optimality conditions and convex optimization. • Use and implement linear quadratic regulators and trackers. • Use receding horizon control and model predictive control algorithms with linear constraints. • Apply predictive control with constraints in renewable energy systems.
Content: • Optimal controller design based on integral criteria • Convex optimization in control systems • Parametric optimization in control systems • Finite and infinite horizon discrete-time linear quadratic regulator (LQR) • Linear quadratic tracking • Basic idea of receding horizon control and model predictive control (MPC) • Constrained linear optimal control (linear and quadratic performance index) • Feasibility and stability of MPC • Parametric solution to the MPC problem • Explicit MPC; Fast MPC Abilities: After completing this course the students will be able to: • Design controller based on integral criteria • Design linear quadratic regulator and linear quadratic tracking for DLTI systems • Design model predictive controller for linear and quadratic performance index with linear constraints • Analyse and ensure stability of MPC • Design explicit solution to the MPC problem
Recommended texts: The notes of the course will be given by the lecturers. **Further readings:** • F. Borrelli et al., Predictive Control for Linear and Hybrid Systems, Cambridge University Press, 2017. • J. B. Rawlings and D. Q. Mayne, Model Predictive Control, Nob Hill Pub, 2009. • S. P. Boyd and L. Vandenberghe, Convex Optimization, Cambridge University Press, 2004. • J. M. Maciejowski, Predictive Control, Pearson Education, 2002.
Keywords: Convex optimization, Linear quadratic regulator, Model predictive control, Receding horizon control, Constrained optimal control
Links with other courses: Linear control systems and Nonlinear control systems from semester 1

Course 3 — Estimation Theory		
Credits: 5	**Summer Semester**	**Compulsory: Yes**
Lectures: 45h	**Tutorial**s: 10h	**Labs:** 12h
Responsible: Ivan PETROVIĆ, Mario VAŠAK, Ivan MARKOVIĆ		
Professors: Ivan PETROVIĆ, Mario VAŠAK, Ivan MARKOVIĆ, Nikola HURE		

Objectives: Estimation theory deals with estimation of system states and parameters from noisy measurements. Methods covered in the course find applications in almost all disciplines and fields of science and technology. The objectives of the course are as follows:

- Introduce basic mathematical concepts in state estimation and system identification from probability theory and stochastic processes.
- Introduce Bayes method and elaborate linear estimation in static and dynamic systems with focus on basic Kalman filter, and then on Extended Kalman filter.
- Understand non-parametric and parametric identification methods for linear systems.
- Adopt the model structure selection and model validation procedures in identification, with understanding of bias-variance conflict in identification.
- Consequently learn importance of grey-box models in which both physical knowledge and estimation of parameters based on data are combined.

Content:

- Basic concepts in estimation, review of background techniques (probability theory and stochastic processes)
- Linear estimation in static system
- Kalman filer and Extended Kalman filter
- Spectral and correlation analysis for non-parametric identification of linear systems
- Parametric models: deterministic ans stochastic parts, least-squares method, direct and recursive, intstrumental variable method
- Procedures for validation of the identified models, bias-variance conflict in identification, grey-box models

Abilities: After completing this course the students will be able to:

- Explain basic concepts in state estimation and system identification and their relation to corresponding mathematical background
- Develop the technique of linear estimation in static systems for corresponding problems
- Use Kalman Kaman filter and Extended Kalman filter in applications linked to renewable energy
- Use non-parametric indentification methods for linear systems in applications leaned to renewable energy
- Use parametric identification methods for linear systems in applications leaned to renewable energy
- Apply bias-variance conflict in grey-box model structuring and validation

Recommended texts: The notes of the course will be given by the lecturers.

Further readings:

- D. Simon, Optimal state estimation, John Wiley & Sons, 2006.
- L. Ljung, System Identification: Theory for the User, Prentice Hall, New Jersey, 1999.

Keywords: Estimation, Bayes method, Kalman filter, Identification, Spectral analysis, Least-squares method, Bias-variance conflict

Links with other courses: Basis for obtaining control-oriented models of renewable energy systems, in which physical knowledge and data from measurements are optimally combined.

Course 4 — Optimal Sizing and Operation of a Photovoltaic System with Storage

Credits: 5	Summer Semester	Compulsory: Yes
Lectures: 30h	**Tutorials:** 0h	**Labs:** 10h

Responsible: Mario VAŠAK

Professors: Mario VAŠAK, Vinko LEŠIĆ

Objectives: Renewable energy systems are complex to size and operate due to their often inherent volatility in production stemming from varying environmental conditions. Their planning and operation needs to be an optimal compromise of costs and gains, which is not easy to assess in such dynamic conditions without a proper mathematical optimization support.The aim of the course is:

- To show how mathematical optimization can be used to support planning the investment in a photovoltaic system combined with a battery storage systems, jointly with deciding on the optimal investment optimal policy.
- Learn simple models of photovoltaic systems and battery storages that can be used in optimization based on energy balance laws, together with main determinants regarding the cost for the corresponding investment and system maintenance, including parts replacement after their lifetime expires.
- Learn the main determinants for assessment of costs/gains for energy exchange with the electricity grid.
- Formulate the models and energy exchange conditions in the form of an optimization criterion and constraints of a mathematical optimization problem for a specific location, characterized with full-year meteorological data, data on yearly profile of energy consumption existing for the location, and possible orientations in which the photovoltaic system can be placed.
- Focus is put on formulation of convex mathematical programs, foremost linear programs which can be used in a similar fashion also for a more general constellation of a renewable energy hub.
- Introduce a possible extension to optimization with nonlinear models of systems and costs by using sequential linear programming.

Content:

- Simple models of photovoltaic systems and battery storages that can be used in optimization based on energy balance laws, computation of yearly production profiles for a specific orientation of the photovoltaic system active surface
- Characterization of the main determinants for assessment of costs/gains for energy exchange with the electricity grid

- Formulation of linear program for investment and operation in a specific location, characterized with full-year meteorological data, data on yearly profile of energy consumption existing for the location and possible orientations in which the photovoltaic system can be placed
- Extension to usage of nonlinear models in optimization – sequential linear programme.

Abilities: After completing this course the students will be able to:

- Apply simple modelling of the photovoltaic system yearly production and battery system charging/discharging
- Express costs and gains related to the photovoltaic system and battery system investments
- Use convex mathematical optimization to formulate and efficiently solve problems of optimal investments sizing and operation for the case of a photovoltaic system with a battery system.
- Know possible extension of the procedure for nonlinear models

Recommended texts: The notes of the course will be given by the lecturer.

Further readings:

- S. Boyd and L. Vandenberghe, Convex Optimization, Cambridge University Press, 2004.
- J. Twidell and T. Weir, Renewable Energy Resources, Routledge, 2021.

Keywords: Photovoltaic system, Battery storage system, Investment cost, Operational gains, Convex optimization, linear program, sequential linear program

Links with other courses: Leans to the Predictive Control course regarding use of optimization in operation planning and control. Leans to Control and Grid Integration Techniques for Renewable Energy Sources regarding grid interaction

Course 5 — Energy-efficient Buildings Control

Credits: 5	Summer Semester	Compulsory: Yes
Lectures: 19h	**Tutorial:** 0h	**Labs:** 12h

Responsible: Mario VAŠAK, Anita BANJAC

Professors: Mario VAŠAK, Anita BANJAC, Nikola HURE

Objectives: Energy consumption in the buildings sector amounts to 30% of overall energy consumed in the world, and thereby buildings consume about 50% of energy on ensuring proper climate conditions in them. Exactly for that reason buildings are a cornerstone of a future zero-carbon energy system: they must integrate a significant amount of renewable energy, foremost solar-based, efficiently consume energy to provide proper comfort and share responsibility in future energy systems regulation through demand response. Control in buildings, especially predictive control, becomes essential in achieving these goals. The objectives of the course are as follows:

- Learn the grey-box modelling approaches for building indoor comfort control.
- Understand the solar resource and its influence on the building indoor climate.
- Use standard PID/hysteresis control techniques for maintaining indoor comfort.

• Apply predictive control for energy-efficient indoor climate control and optimal coupling with building renewable energy sources in energy market participation and demand response provision.
Content: • Illustrative and motivating example of a smart building – demonstration of UNIZGFER skyscraper building operation. • Modelling of heat transfer processes in buildings with grey-box simplifications • Modelling of a solar resource: direct, diffuse, reflected and total solar irradiance on a tilted surface. • Modelling of zone-level and central heating/cooling elements in buildings with grey-box simplifications • Standard control structures of indoor comfort in buildings • Application of predictive control to thermal comfort control in buildings: use of linear programming • Basic principles of demand response in buildings and its predictive control based implementation **Abilities:** After completing this course the students will be able to: • Summarize the structure of the system for ensuring indoor climate in buildings in analysis of building operation • Understand the solar resource influence on building indoor climate • Apply PID/hysteresis control in indoor climate control in buildings • Apply predictive control in indoor climate control in buildings, its matching with renewable energy production, in energy market participation and demand response
Recommended texts: The notes of the course will be given by the lecturer. **Further readings:** • S. Boemi et al., Energy Performance of Buildings, Springer, 2016.
Keywords: Building indoor climate control, Thermal grey-box modelling, Solar irradiance, Standard control, Predictive control, Demand response
Links with other course: Grey-box modelling from Estimation theory, PID/hysteresis control from Linear control systems, Predictive control from Predictive control course. Solar resource for Control and grid integration techniques for renewable energy sources. Demand response basics (grid-side perspective) from Control and grid integration techniques for renewable energy sources

Course 6 — Project on Control, Estimation and Optimization in Solar Energy		
Credits: 3	**Summer Semester**	**Compulsory: Yes**
Lectures: 19h	**Tutorial:** 0h	**Lab:** 12h
Responsible: All tutors at UNIZGFER		
Professors: All tutors at UNIZGFER		
Objectives:		

Extend study on a specific topic within the area of control, estimation and optimization for solar energy systems, improve presentation and communication skills, as well as writing skills by discussing selected topics with other students, teachers and industry/academia associates.

Students will present, within small groups, latest concurrent developments in the area which they will back with practical examples elaborated by them. Each student will explore and present one of the topics agreed on with the selected supervisor.

Content:

- Independent assignments
- Work with tutor
- Preparation of written report and of a presentation
- Presentation of the work in front of a group of students, teachers and academic/industry associates

Abilities: After completing this course the students will be able to:

- Describe in concise written report actual topics from the profession and science
- Match facts from recommended literature with knowledge gained during studies
- Describe and summarize given topic in front of a group of listeners
- Critically evaluate quality of presentations of other students
- Prepare a report in accordance with publishing standards in professional and scientific publications
- Apply gained knowledge of communication skills for public presentation of a given topic
- Evaluate the appropriateness of different solutions within a given specific topic

Recommended texts and further readings:

Provided to the student on case-by-case basis from the selected supervisor.

Keywords: Individual assignment, Control, Estimation, Optimization, Solar energy systems, Written report, Presentation

Links with other courses: Linked with all other courses in the semester where the student gets a basic knowledge on a certain topic further detailed in this course. Linked also with Linear control systems and Nonlinear control systems from the first semester.

Syllabus of courses offered in Brandenburg University of Technology Cottbus-Senftenberg

Course 1 – Geothermal Energy		
Credits: 6	Fall Semester	Compulsory: No
Lectures: 24h	**Tutorials:** 12h	**Lab:** 0h
Responsible: Prof. Dr. Mario Ragwitz / Institut für Eleketrische und Termische Energiesysteme		
Professor: Prof. Dr. Mario Ragwitz / Institut für Eleketrische und Termische Energiesysteme		
Objectives: This course provides an overview of geothermal technologies and their application for the generation of electricity, heating & cooling and for underground thermal energy storage. Understand the geothermal heat source, properties of the subsurface and thermal transfer mechanisms. Apply knowledge to the basic design of local heat distribution systems, the integration of low temperature geothermal heat sources and ground-source heat pumps in the energy supply systems and the use of geothermal storage options for the balancing of seasonal heating & cooling demands with asynchronous supply and demand cycles as well as the basic economic considerations of geothermal energy generation and heat network integration.		
Content: • Basic geological principles • Overview of different geothermal systems • Geothermal fluids – thermal and chemical properties • Heat transfer in the subsurface • Reservoir characterization • Design of a geothermal system • Geothermal electricity: historical development, types of power plants • Geothermal heat usage: residential heating, industrial applications • Environmental issues of geothermal energy • Geothermal heat networks • Integration of ground-source heat pumps in flexible heat supply systems • Economics of geothermal energy and heat networks/district heating • Support schemes for geothermal energy and heat networks/district heating		
Recommended texts and further readings: • R. di Pippo: Geothermal Power Plants Principles, Applications, Case Studies and Environmental Impact 4th Edition, Elsevier, 2015 • George L. Danko: Model Elements and Network Solutions of Heat, Mass and Momentum Transport Processes, Springer-Verlag GmbH. 2016.		
Keywords: Geothermal, power plants, design, heat networks		

Course 2 – Hydrogen and Fuel Cells		
Credits: 6	**Fall Semester**	**Compulsory: No**
Lectures: 30h	**Tutorial:** 15h	**Lab:** 0h
Responsible: Prof. Dr. Lars Röntzch / Institut für Elektrische und Termische Energiesysteme		
Professor: Prof. Dr. Lars Röntzch / Institut für Elektrische und Termische Energiesysteme		
Objectives: Students are introduced to the complete chain of hydrogen energy technology, from hydrogen production storage and distribution to its use. In each chapter, the course deals with the physicochemical working principles underlying the respective hydrogen technologies, an in-depth description of the technology (including selected material and production aspects) and its application using practical examples		

Content:

1. Introduction to hydrogen and its properties
2. Hydrogen energy cycle
3. Hydrogen production
   - Overview
   - Steam reforming of natural gas and other non-renewable feedstock's
   - Low-carbon production of hydrogen from fossil fuels
   - Reforming of bio-alcohols and gasification of biomass
   - Production of hydrogen through electrolysis (AEL, AEMEL, PEMEL, SOEL)
   - Photo electrochemical and photo biological methods
   - Thermochemical water splitting
   - Kværner process and plasma reforming
4. Hydrogen purification
   - Overview
   - Redox processes
   - Adsorption and absorption
   - Polymeric membranes
   - Metallic membranes
5. Hydrogen storage
   - Overview
   - Hydrogen liquefaction and liquid hydrogen storage
   - Slush hydrogen production and storage
7. Fuel cells
   - Overview
   - Proton exchange membrane fuel cells
   - Phosphoric acid fuel cells
   - Molten carbonate fuel cells
   - Solid oxide fuel cells
   - Reversible fuel cells
   - Microbial and enzymatic fuel cells
   - Fuel cell systems for mobile applications
   - Fuel cell systems for stationary applications
   - Micro fuel cell systems
8. Hydrogen combustion
   - Overview
   - Hydrogen-fuelled internal combustion engines
   - Hydrogen-fuelled turbines
   - Catalytic combustion of hydrogen
9. Hydrogen use
   - Hydrogen-fuelled road vehicles (passenger cars, trucks, buses)
   - Hydrogen-fuelled trains
   - Hydrogen-fuelled marine transportation
   - Hydrogen-fuelled aeroplanes and space crafts
   - Portable hydrogen applications
   - Hydrogen industrial use (steelmaking, chemical industry)

- Compressed hydrogen storage
- Underground and pipeline hydrogen storage
- Cryo-compressed hydrogen storage
- Hydrogen storage by adsorption processes
- Solid hydrogen carriers
- Chemical hydrogen carriers (LOHC, NH3, MeOH)
- Thermochemical cycles

6. Distribution and infrastructure
   - Overview
   - Pipeline transportation
   - Trailer transportation
   - Designing optimal infrastructures for delivering hydrogen
   - Hydrogen refilling stations for FCEV

- Re-electrification of hydrogen
- Hydrogen-based decentralized power supply

10. Hydrogen safety
    - Overview
    - Sensors and detectors
    - Hydrogen embrittlement
    - Hydrogen safety engineering
    - Design, commissioning and maintenance of hydrogen plants
11. Hydrogen technology implications
    - Economics of hydrogen
    - Legal aspects of hydrogen
    - Hydrogen and the environment
    - Political and social impacts of hydrogen energy

Recommended texts and further readings:

- Compendium of Hydrogen Energy, Volumes 1-4 (Woodhead, 2015).
- Hydrogen - Its Technology and Implications, Volumes 1-5 (CRC Press, 2018).
- Fuel Cells and Hydrogen Production (Springer Science, 2019).
- Hydrogen Energy - Challenges and Solutions for a Cleaner Future (Springer, 2019).
- Hydrogen Production Technologies (Wiley, 2017).
- Handbook of Hydrogen Energy (CRC Press, 2014).
- Hydrogen Safety (CRC Press, 2013).

Keywords: Hydrogen Combustion Hydrogen Safety, Low-Carbon Fuels, Hydrogen Career, Fuel Cells

Course 3 – Chemical and Thermal Energy Storage

Credits: 6	Fall Semester	Compulsory: No
Lectures: 2h per week	**Tutorial:** 2h per week	**Lab:** 0h

Responsible: Prof. Dr. Ing. Fabian Mauß / Institut für Elektrische und Termische Energiesysteme

Professor: Prof. Dr. Ing. Fabian Mauß / Institut für Elektrische und Termische Energiesysteme

Objectives: The lecture deals with electrochemical and chemical processes which are important for renewable energy storage and conversion. The lecture incorporates recent research from the Energy Innovation Center of BTU Cottbus-Senftenberg. Students acquire in-depth knowledge of thermodynamic processes, the reaction mechanisms of electro-catalysis, turbulent combustion of fuels and measurement devices to characterize surface and gas phase reactions. They are familiar with the simulation of the teached processes.

Students gain in-depth knowledge of the subject area and are able to make scientifically sound judgments.

Content: Introduction to electro-chemical energy storage and conversion

- Power-to-X-to-Power energy and substance cycles
- Energy balances and efficiencies
- Environmental impact

Electrochemistry

- Fundamentals
- Electrode reaction and Butler-Volmer equation
- Impednae spectroscopy
- Electrolysis
- Lithium-Ion-Battery
- Simulation

Synthesis & Conversion

- Heterogeneous catalysis
- Reactor types
- Power-to-X-to-Power processes
- Industrial applications
- Surface spectroscopy
- Modelling & Simulation

Kinetics & Spectroscopy

- Transition State Theory (TST), Thermodynamic Formulation of TST
- Unimolecular Rate Theory Beyond Lindemann Mechanism
- Introduction to Spectroscopy and Laser Diagnostics for Gases (diatomic polyatomic Spectra, quantitative emission and absorption, LIF and its application)

Recommended texts and further readings:

- The lectures notes will be provided

Keywords: Electro-chemical Energy Storage, Electrolysis, Batteries, Power-to-X-to-Power processes, Spectroscopy

Course 4 – Control of Power-to-X, Storage and X-to-Power Systems		
Credits: 6	**Fall Semester**	**Compulsory: No**
Lectures: 2h per week	**Tutorial:** 2h per week	**Lab:** 0h
Responsible: Prof. Dr.-Ing. Johannes Schiffer / Institut für Elektrische und Termische Energiesysteme		
Professor: Prof. Dr.-Ing. Johannes Schiffer / Institut für Elektrische und Termische Energiesysteme		

Content:

- Control-oriented modelling of power-to-X components, such as heat pumps and electrolyzers of storage units and of X-to-power components, e.g. fuel cells

• Description of typical control and operational objectives from the point of view of the plant owner as well as the grid operator (as specified, e.g. in grid codes) • Controller synthesis for power-to-X, storage and X-to-power systems • Derivation of optimal control and operation strategies for enhanced operational performance and flexibility • Extension of the control architecture to provide ancillary services to the electric grid, such as virtual inertia and voltage and frequency support.
Learning Outcome: On the completion of this module, students should be able to: • Model power-to-X, storage, and X-to-power systems from a control-oriented perspective • Select a suitable control architecture and design controllers for such systems • Characterize the behaviour of the closed-loop system from the point of view of the plant owner as well as the grid operator
Course prerequisites: The students are expected to have prior knowledge in: • Mathematics • Physic • Control Engineering 1 (or equivalent
Keywords: Power-to-X, storage, and X-to-Power systems, Modelling, Control, Optimal control