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About TeacHy

As the FCHT industry gradually emerges into the markets, the need for trained staff becomes more pressing. TeacHy2020, or short TeacHy, specifically addresses the supply of undergraduate and graduate education (BEng/BSc, MEng/MSc, PhD etc.) in fuel cell and hydrogen technologies (FCHT) across Europe.

TeacHy2020 will take a lead in building a repository of university grade educational material, and design and run an MSc course in FCHT, accessible to students from all parts of Europe. To achieve this, the project has assembled a core group of highly experienced institutions working with a network of associate partners (universities, vocational training bodies, industry, and networks). TeacHy offers these partners access to its educational material and the use of the MSc course modules available on the TeacHy site. Any university being able to offer 20 to 30% of the course content locally, can draw on the other 80 to 70% to be supplied by the project (and its successor entity that will support the platform post-project).

This will allow any institution to participate in this European initiative with a minimised local investment. TeacHy will be developing solutions to accreditation and quality control of courses, and support student and industry staff mobility by giving access to placements. Schemes of Continuous Professional Development (CPD) will be integrated into the project activities. We expect a considerable leverage effect which will specifically enable countries with a notable lack of expertise, not only in Eastern Europe, to quickly be able to form a national body of experts.

TeacHy will offer some educational material for the general public (e.g. MOOC’s), build a business model to continue operations post-project, and as such act as a single-stop shop and representative for all matters of European university and vocational training in FCHT. The project partnership covers the prevalent languages and educational systems in Europe. The associated network has over 70 partners, including two IPHE countries, and a strong link to IPHE activities in education.

Abstract

The present document describes the contents of the whole course on fuel cell and hydrogen technologies (FCHT). The course is organised into several modules: seven (7) are mandatory for the students, while eleven (11) are optional. The titles of mandatory courses are listed below:

1. ***Introduction to fuel cells***
2. ***Thermodynamics, electrochemistry and chemistry***
3. ***Characterisation methods***
4. ***Fuel Cells modelling tools and control***
5. ***Hydrogen, fuels, electrolysers***
6. ***Labs***
7. ***Hydrogen safety***

While the following optional modules are proposed to students:

1. ***Environmental analysis, life cycle analysis***
2. ***Low temperature fuel cells***
3. ***High temperature fuel cells***
4. ***Low temperature systems***
5. ***High temperature systems***
6. ***Advanced characterisation***
7. ***High temperature chemistry for SOFCs/SOECs***
8. ***Fuel cell electric vehicles***
9. ***Politics, markets, regulation, codes and standards***
10. ***Energy system and storage***
11. ***Advanced modelling***

Two ‘additional’ modules have been developed for use in MSc courses exceeding 12 to 18 months duration as additional study material:

1. ***Electrocatalysis***
2. ***Power to Gas***

For each module a detailed description of the scientific and teaching contents is provided in this document. Each module is individually displayed through summaries of lecture material. In some cases, partners also provided the time duration in hours of the lectures and other details.

1 Introduction

The material for a whole course dealing with hydrogen and fuel cells (FC) should cover a wide range of notions and fundamentals: from pure sciences as chemistry, physics, maths and material science to engineering, policy and economics. The MSc course proposed within the TeacHy project has the purpose to cover all these aspects and topics through a series of modules. Some of them are mandatory for students as they cover and present fundamental aspects of hydrogen and fuel cells.

Firstly, ‘Introduction to fuel cells’ module present an introductory overview of the subject. Hydrogen is usually exploited for power production through fuel cells that are electrochemical devices.

An insight on base chemistry from a pure science standpoint is thus required. The theoretical background to students is provided via ‘Thermodynamics, electrochemistry and chemistry’ module.

‘Characterisation methods’ module describes the electrochemical behaviour of fuel cells, covering also some aspects of construction and operation. Techniques for constituent materials characterisation and lifetime degradation are described.

In ‘Fuel Cells modelling tools and control’ an overview of simulation techniques to reproduce the steady-state and/or transient behaviour of FC is provided. Balance/conservation equations are discussed for mass, momentum and energy (keeping in mind the analogy between transport phenomena). The module is organised to offer a general overview followed by application to low-temperature and high-temperature fuel cells. A multiscale approach is proposed for modelling: from the single active site or catalyst particle to the whole FC-based plant (including balance of plant and auxiliaries).

‘Hydrogen, fuels, electrolysers’ module focuses on the fundamentals of hydrogen production and utilisation. This module combines a variety of disciplines from area of hydrogen production, storage, transport or delivery. Hydrogen can be used as final fuel in FC but can be also an intermediate carrier to produce synthetic fuels as methane, methanol or dimethyl ether, representing a valuable option for renewable energy storage in a chemical form.

The ‘Labs’ module focuses on experimental apparatus for practical investigation on hydrogen and fuel cells technologies. It consists of a descriptive part with theoretical and practical background behind the experiments. Moreover, the students will have the possibility to make tests on site and remotely. The module is organised in two sub-modules: in the first one each partner can provide an overview of the experiments that can be carried out with their facilities. The second one is focused on a remote experimental apparatus that POLITO is going to make available to the whole consortium (but also to external partners).

Hydrogen presents a wide flammability range: special care is required in its management (storage and use). ‘Hydrogen safety’ module is developed to enable the student to understand the origin and phenomenology of hydrogen safety problems as unscheduled releases and dispersion of jets, ignition mechanisms, flames, jet fires and associated hazard distances.

Other modules are optional for students. Some of these modules are insights of the topics covered within mandatory courses (‘Advanced characterisation’, ‘Advanced modelling’ and ‘Energy system and storage’). Other optional modules cover the distinction between two categories of electrochemical devices to exploit hydrogen for electricity production: high and low temperature fuel cells (‘Low temperature fuel cells’, ‘High temperature fuel cells’, ‘Low temperature systems’, ‘High temperature systems’ and ‘High temperature chemistry for SOFCs/SOECs’). ‘Environmental analysis, life cycle analysis’ module focuses on direct and indirect carbon dioxide emissions related to hydrogen production and fuel cells operation. Another module is devoted to application of FC to automotive instead of electricity generation (‘Fuel cell electric vehicles’ module). Finally, ‘Politics, markets, regulation, codes and standards’ presents technical and non-technical aspects related to RCS, market analysis and political perspectives of hydrogen and fuel cells technologies.

Two additional modules (‘Electrocatalysis’ and ‘Power to Gas’) have been proposed and developed. These modules focus on the complex aspects for real electrochemical systems: role of the double layer, complex redox mechanisms. The lectures provide an overview of interfacial electrochemistry and outlines the mechanisms of electrocatalysis for those studnts wishing to deepen their knowledge in this area. Likewise, the P2G module further develops the strategies behind P2G and reversible fuel cell technologies and looks into the applications and implications of the technology.

1.1.1 Granularity and reusability

The modules that make up the course regularly consist of about 12 to 15 lectures lasting 2 nominal hours each (in two sections of 45 to 50 minutes length). Each lecture has been prepared as a power point presentation which was recorded via Panopto or other systems to deliver a video file. These files were uploaded onto the UBHAM CANVAS platform in order to assemble the first test course as a blueprint for further implementations at other universities and other platforms and/or on the NET-Tools platform.

The module structure segmented in individual lectures ensures that each lecture can be considered as *per se* (avoiding a too strict connection with the other module material). Furthermore, each presentation can be reused for other purposes, as teaching material for different levels (bachelor, master or doctoral) or for CPD programmes. The produced material can be also used, in some cases, as introduction to other topics not necessarily linked to fuel cells (e.g. transport phenomena, batteries, renewable energy etc.). The required academic level demanded in the accreditation processes will not always allow a seamless transfer to CPD, undergraduate or MOOC applications. Nevertheless, the original PPT slide sets are available within the consortium to be modified and re-recorded for other than MSc course deployment. As the base material remains the same, re-usability of refinements both on the MSc course side and when tailored to other contexts will benefit the quality of the teaching material. Besides having versions of lectures in different languages it is also imaginable that different versions of the same lecture might be available for different audiences.

2 Mandatory modules

2.1 C1 - Thermodynamics, electrochemistry, chemistry (KIT, Grenoble INP)

2.1.1 Module content development

The section shall introduce into the fundamentals and basic principles as far as inevitable for a comprehensive and detailed understanding of the specific theme hydrogen technologies and fuel cells. Thermodynamics, electrochemistry and inorganic chemistry overlap thematically, which should be exploited to develop these parts not independently from each other but rather building on each other. Thus, thermodynamics shall include and explain terms which are essential in electrochemistry and inorganic chemistry such as energy, entropy, enthalpy etc. but also terms such as systems and system boundaries and their meaning or extensive and intensive variables in details. Thus, the focus is on the terms used, their direct meaning and interrelations and, ultimately, their mathematical formulation. To explain more detailed the different approaches, further explanations on important content will get subdivided into:

- Thermodynamics
- Inorganic Chemistry
- Electrochemistry

This module consists of 35 lectures @ on average 45 minutes each.

2.1.2 Thermodynamics

<u>Thermodynamic Theories and its History</u>
Introduction to thermodynamic theories shortly, including brief history of the development of single thermodynamic theories, the fundamentals and mathematical formulation, to gain understanding in the different approaches arising from different theories and different applicability. It shall get introduced to:

- History and development over the centuries
- Classical Thermodynamics
- Statistical Thermodynamics
- Chemical Thermodynamics
- Equilibrium Thermodynamics
- Gibbs Fundamental Relation
    - $U = U(S, V, n)$
    - Complete differential (mathematical formulation and definition)
    - $dU = \left(\frac{\partial U}{\partial S}\right)_{V,n} dS + \left(\frac{\partial U}{\partial V}\right)_{S,n} dV + \left(\frac{\partial U}{\partial n}\right)_{V,S} dn$
    - All equations of state in principle first derivations of Gibbs Fundamental Relation

The basic findings of the respective theory will get explained and differentiated from each other.

<u>Thermodynamic Systems</u>
General approach on how to define thermodynamic systems, the limitation of systems, the periphery and its boundaries. Also important to introduce some thermodynamic notation and specific terms to distinguish variables e.g. intensive and extensive variables which shall get included.

- Definition of systems and describing variables
- Closed and thermodynamic systems

- permits energy transfer
- Open thermodynamic systems
  - permits mass and energy transfer
- Isolated thermodynamic systems
  - permits no mass and no energy transfer through boundaries
- Surroundings of systems (standard conditions included)
- Boundaries and conditions of systems (thermodynamic variables)
- Intensive and extensive variables (distinctions od state variables)
- Interactions of systems (change of state variables)
- Unitary systems and multicomponent systems

General Laws of Thermodynamics

This section is essential to understand thermodynamics on a fundamental basis, physical as well as mathematical basis.

- Zeroth law of thermodynamics
  - equilibrium of systems in thermal contact
- First law of thermodynamics
  - $\Delta U = \Delta Q + \Delta W$
  - conservation of energy
- Second law of thermodynamics
  - directions of processes and irreversibility
  - terms like entropy, exergy, anergy
  - $Q_H = W + Q_C$
  - efficiency $\eta = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$
  - Carnot 's formulation $\eta_{max} = 1 - \frac{T_C}{T_H}$
- Third law of thermodynamics
  - impossibility to get to absolute Zero Point of temperature

Thermodynamic Processes

Important to explain the principles of simple thermodynamic processes depending on the variables. Also it appears essential to get learned about the specific terms of processes and notation. Additionally, important notation like “entropy”, “enthalpy” will get introduced on a basic level easy to understand.

- Introduction (Systems and Process)
- Adiabatic process (without loss or gain of energy by heat)
- Isenthalpic process
  - constant enthalpy $H = U + pV$
- Isentropic process
  - reversible adiabatic process, constant entropy $dS = \frac{\delta Q_{rev}}{T}$
- Isobaric process
  - constant pressure
- Isochoric process
  - constant volume (also called isometric/isovolumetric)
- Isothermal process
  - constant temperature $T = \left(\frac{\partial U}{\partial S}\right)_{V;N}$
- Steady state process
  - without change in the internal energy

Thermal Equation of State of Ideal Gases

Introduction to the specific laws of thermodynamics its relations and interconnections to understand the principles of thermodynamics as single specific themes are:

- General introduction
- Law of Boyle-Mariotte
- Law of Gay-Lussac
- Law of Amontons
- Law of Conformity
- Law of Avogadro

Ideal gas law should get introduced as a single chapter due to the facts that basic understanding to thermodynamics could get reached by understanding “ideal gas law” as an idealistic point of view to discover the differences between ideal and real gas behaviour. The distinction regarding the behaviour of different substances (especially in gaseous state) can get best explained by applying to the “ideal gas law” and other equations of state. This leads to the understanding of using different equations and factors to correct results arising from ideal gas law.

- Derivation of ideal gas law from classical and kinetic gas theory
    - $T = \frac{\partial U}{\partial S}$, $p = -\frac{\partial U}{\partial V}$, $pV = nRT$

- Aberrations of perfect gases from ideal gas law
    - real gas factor $Z = \frac{pV}{nRT}$
    - ideal gas $Z = 1$
    - real gas $Z = f(p, T)$
    - consequences (e.g. Joule Thompson effect and Joule Thomson coefficients)
    - liquefaction of real gases
- Equations of State (real gas behaviour)
    - Van-der-Waals equation
        - Attractive and repelling terms
        - Van-der-Waals coefficients
    - Viral equation
        - Development in Power Series
        - Viral coefficients
    - equation of state diagrams (basic diagrams and comparison of diagrams)
- Critical points (based on Van-der-Waals equations)
    - state of aggregation
    - T-P-diagrams (inversion curves)
    - Van-der-Waals equation (to calculate critical points)

Thermodynamic Cycles

It is essential to introduce into thermodynamic cycles (idealistic and realistic) concerning the principles of liquefaction and efficiency coefficients

- Carnot Cycle (idealistic)
    - Reversible isothermal expansion of the gas at the "hot" temperature, T_H (isothermal heat addition or absorption)
    - Isentropic (reversible adiabatic) expansion of the gas (isentropic work output)
    - Reversible isothermal compression of the gas at the "cold" temperature, T_C. (isothermal heat rejection)
    - Isentropic compression of the gas (isentropic work input)

- Carnot's Theorem
  - $\eta_{max} = 1 - \frac{T_C}{T_H}$
- Efficiency of real engines
  - $\eta < \eta_{max}$

<u>Liquefaction of Gases</u>
The paragraphs "gases" and "thermodynamic cycles" were introduced due to the basic understanding of liquefaction of gases, especially hydrogen.

- Joule Thompson Effect
  - Joule Thompson coefficient $\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_H$
  - positive and negative Joule Thompson coefficient
  - effects related to the values
  - T-S Diagram and Inversion curve
- Linde Process
  - positive coefficient (liquefaction of air, oxygen, nitrogen)
  - negative coefficient (cooling down of hydrogen and helium)
  - technical assembly and functioning
- Ortho- Para Hydrogen
  - Spin system and constitutions
  - Distribution ortho- para- hydrogen under different conditions
  - Ortho- para- shift
  - relations to liquid hydrogen "Norm-Hydrogen"

2.1.3 Inorganic Chemistry

This section is not intended to teach the basics of inorganic chemistry. Rather, special reaction mechanisms and processes are to be described, which make essential formulations (reaction equations) and the chemical behaviour of the substances mutually understandable.

<u>Introduction Period System, Substances and Basic Chemical Reactions</u>
This section shall give an overview about substances and order within Period System. A multitude of reactions play a role in inorganic chemistry. The most important of these are the redox reactions and the acid-base reactions. Especially the paragraph about redox reactions shall get used to lead over from inorganic chemistry to electro-chemistry. These reactions are always equilibrium reactions, but the equilibrium of these reactions is often very strong on one side and there is a high enthalpy of reaction. As a result, many reactions in the inorganics are fast and achieve a high yield which shall get instructed as such.

Redox reactions are reactions in which electrons are transferred from one reaction partner to the other. Typical redox reactions are reactions of elements to compounds. The best-known redox reactions are the oxyhydrogen-oxygen-hydrogen-corrosive reaction with water and the corrosion in which base metals (e.g. iron) react with oxygen to form oxides.

Acid-base reactions are reactions in which protons are transferred. The acid releases a proton to the base (also: lye). In acid-base reactions, water and a salt are usually formed (the best known example is the reaction of hydrochloric acid with sodium hydroxide solution to form sodium chloride and water). Since these reactions take place very quickly and can be precisely monitored with indicators, they play a major role in analytical chemistry.

In inorganic chemistry, the formation of particularly stable salts or gaseous compounds is an important driving force for reactions. From solutions containing ions, particularly stable salts can precipitate in a precipitation reaction. The inorganic substances can be divided into several large substance groups. These are:

Metals and semi-metals: Metals include a large proportion of the elements of the periodic table (approx. 80 %). Common metal properties are the conductivity for heat and electricity. Examples of metals are iron and sodium. Semimetals have both metallic and non-metallic properties. They stand in the periodic table between metals and non-metals. Examples are silicon and germanium.

Intermetallic compounds, the so-called alloys: Alloys are compounds of metals with each other. They are obtained from metals because of special properties (e.g. special hardness or toughness). Well-known alloys are bronze (made of copper and tin) and steel (iron alloys with different admixtures).

Salts: Salts have an ionic structure and consist of positively charged cations and negatively charged anions. Cations are mostly metal ions, anions are mostly non-metal ions. Known salts are sodium chloride Na^{+}, Cl^{-} and the oxides where oxygen is the anion.

Non-metal compounds that do not contain carbon: These are covalently formed compounds formed by non-metals (e.g. oxygen or nitrogen) with each other. Of the covalent carbon compounds, only very few that do not contain hydrogen belong to inorganic chemistry, all others to organic chemistry. These are mainly carbon monoxide and carbon dioxide. The best known of these compounds is water.

Inorganic compounds are usually built up periodically or from a small number of atoms. Metals, alloys and salts are built up periodically, instead of a sum formula only a ratio formula can be given. Inorganic covalent compounds - in contrast to most organic compounds - are usually small and composed of only a few atoms. Higher molecular compounds are rare, for example in silicon chemistry. As far, it is not foreseen to introduce in further reaction mechanism or chemical compounds.

Acid-Base-Systems

An introduction to gain knowledge about acids and alkali systems and its behaviour to each other, simple calculations to calculate also pH-value

- Common acid-base theories
  - Lavoisier definition
  - Liebig definition
  - Arrhenius definition
  - Brønsted-Lowry definition
  - Lewis definition
  - solvent-system definition

The next section about will get used to lead over to the electro-chemistry.

Redox Reactions

Redox reactions are of fundamental importance in chemistry and fuel cells. Every metabolic and combustion process, many technical production processes and many detection reactions are based on such electron transfer reactions. Specifically following themes will get tackled more detailed to explain the fundamentals and gain understanding of such reaction mechanism.

- Oxidising and reducing agents
- Examples of redox reactions
- Redox reactions in industry
  - Redox cycling
- Balancing redox reactions
  - acid medium
  - basic medium

2.1.4 Electro-Chemistry (3 lessons)

In general, electrochemistry deals with situations where oxidation and reduction reactions are separated in space, connected by an external electric circuit. Thus electrochemistry will get developed as a branch of chemistry that studies chemical reactions which take place at the interface of an electron conductor (the electrode composed of a metal or a semiconductor, including graphite) and an ionic conductor (the electrolyte) and which involve electron transfer between the electrode and the electrolyte.

The section shall get based on the principle that if a chemical reaction is caused by an external voltage, as in electrolysis, or if a voltage is caused by a chemical reaction, as in a battery, it is an electrochemical reaction. However, batteries will not be object of this section. Chemical reactions where electrons are transferred between atoms are called oxidation/reduction (redox) reactions. An understanding about redox reaction became already included in the above section. In general, electrochemistry deals with situations where oxidation and reduction reactions are separated in space, connected by an external electric circuit. Fuel cells and oxidation of metals will be not scope of this section. Fuel cells can get named but will get taught much more detailed elsewhere. More detailed the content to be developed will follow the list below:

Lesson 1 : Introduction to electrochemistry

- History
  - important developments over the history
  - 20th century and recent developments
- Principles
  - redox reactions (short summary)
  - oxidation and reduction
  - Nernst Equation

Lesson 2 : Electrochemical chain, electrochemical cells

- Standard electrode potential
- Spontaneity of redox reaction
- Cell dependency on changes in concentration

Lesson 3 : Fuel and electrolysis cells

- Concentration cells
- Fuel cells
- Electrolysis cells

Further teaching material will be developed to provide for especially

- Electrochemical voltage series
- Membrane potential

It is envisaged to complete this section with specific but short and single introductions to important equations used to calculate fuel cells.

- Free enthalpy and cell voltage
- IUPAC convention
- Daniell element
- Cell voltage derived from thermodynamic data (Gibbs-Helmholtz Equation)
- Temperature dependence of cell-voltage
- Pressure dependence of cell-voltage
- Thermodynamic efficiency compared to electrochemical based calculation
- Thermo-neutral voltage
- Some more on suggestions

At least, each section shall conclude with specific examples to applications, sample calculations easy to transfer and references to e-learning content (if available) but also to other teaching materials.

2.1.5 Learning outcomes

The module will allow the students to be able to

- Apply the methods and techniques learned to review, extend and apply their knowledge and understanding, to initiate and perform short projects;
- Critically evaluate arguments and data, to construct judgements and appropriate questions to enable a solution (or solutions) to a problem to be reached;
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

2.2 C2 - Fuel cell Technology (UBHAM)

2.2.1 Module content

The Introductory Module will set the stage for all following syllabus elements in that it will introduce the applications of fuel cells, also touching briefly on electrolysers and fuels, to put all other scientific and technical content into context.

The FCT module is based on the 4th Year Chemical Engineering (MEng) and Centre of Doctoral Training (CDT) module accredited at University of Birmingham. This is the introductory module for the taught element of the 4-year PhD programme. It is taken by 30 to 50 students annually. All modules at University of Birmingham are concluded by a summative assessment in the shape of an exam. In addition, a coursework report on the design of a fuel cell system of the choice of the student is required. Both elements count 50% each into the final mark.

A similar approach will be adopted here, with an exam paper and a research report being the assessment components in this module.

It is recommended that this module is run in face-to-face mode, since it will allow much scope for students asking questions and actively discussing teaching content.

The module consists of 8 lectures introducing the topics listed in more detail below.

Module overview: The Introductory module aims to introduce Fuel Cell Technologies (FCT) to students and provide them with the basic science behind the processes involved. This will be a useful basic start for the students to understand the following, more detailed and complex modules. It is also intended to give some background and insight into topics that will later be explored in more detail or are covered in optional modules so that all students have at least a set of very basic knowledge on the broad range of topics covered in the course.

Sustainable and Renewable Energy Future (2 lessons = 2 x 50 minutes)

This lecture is meant to give the students a background on the importance of sustainability as a concept in designing engineering systems for the future. A systems view is introduced in order to introduce the context engineering design work operates in and explain the increasing limitations posed by climate change and world economic development. Topics to be discussed include:

- world energy needs, carbon dioxide emissions, and economic development,
- fossil energy reserves and resources, ranges, and future developments,
- the 2 kW society concept, the cost of climate change,
- implementation of renewable energies and the need for storage technologies,
- use of hydrogen and fuel cells for renewable energy storage, power-to-x technologies.

A basic introduction to Electrochemistry and Thermodynamics (2 lessons = 2 x 50 minutes)

This lecture applies the basics covered in Module C1 and applies it to fuel cell and electrolysis technology. It gives the students the opportunity to relate the theoretical content of C1 to the key functions of FC/ELY equipment, understand the reversibility of processes and quickly judge the efficiency, suitability, and performance of devices using the thorough understanding of their basic functions they receive in this lecture.

Coursework Introduction (1 lesson, 45 minutes)

The coursework consists of a simple design task put to the students:

to devise a fuel cell application (based on the coming lecture material) and do the basic engineering design calculations for this application. The lecture explains the format expected and gives some guidelines as to how the students should perform their work task, also providing a general structure and headlines for the report. Some examples from past coursework are presented in order to illustrate the task.

We expect a report of around 5,000 to 7,500 words (10 to 15 pages), but there are no formal limits. The report is expected to be complete in covering the following topics:

- the application and its justification (why is this a sensible application? what are the benefits a fuel cell would offer?),
- a design exercise calculating key indicators such as power, fuel demand, energy balances etc., also including more detailed analysis of FC stack or system details, if the students so wishes to do,
- a presentation of a 'business case' for the application, especially if it is not competitive currently, showing alternate pathways to market.

The two following lectures give the students a first introduction to technology and applications of fuel cells operating below and above 200°C. The intention is to lay the basis of a broad overview that will help understand the more detailed modules later in the course. Students will be able to place information in context more easily and be able to understand differences in technologies that make some fuel cells more or less viable for specific applications. Supplying this information early will support students building a general understanding of FCT and help them formulate questions that can be discussed in the lectures (in case of face-to-face delivery) or discussion fora (if online-delivered).

Low Temperature Fuel Cells (2 lessons = 2 x 50 minutes)

For the following introduction of LTFC types information will be given on history, basic functions and electrochemistry, and applications, respectively. The lecture gives a basic introduction to

- characteristics of LTFC,
- Alkaline Fuel Cell, AFC,
- Phosphoric Acid Fuel Cell, PAFC,
- Polymer Electrolyte Fuel Cell, PEFC (also including details of electrode structure, stacking, and water management, as well as current research topics)
- i-V curves and performance comparisons
- High Temperature PEFC, HT- and IT-PEFC,
- Direct Methanol Fuel Cell, DMFC.

High Temperature Fuel Cells (2 lessons = 2 x 50 minutes)

For the following introduction of HTFC types information will again be given on history, basic functions and electrochemistry, materials, and applications, respectively. The lecture gives a basic introduction to

- characteristics of HTFC and fuel processing,
- Solid Oxide Fuel Cell, SOFC,
- geometries, interconnects, i-V curves,

- system issues and carbon formation

- Molten Carbonate Fuel Cell, MCFC.

Reversible Fuel Cells (2 lessons = 2 x 50 minutes)

Due to the increasing importance of reversible operation of fuel cells, i.e. turning the same device into an electrolyser, a lecture on rFC has been introduced here. This is an example of a lecture that could also be used relatively straightforward in a CPD course or adapted to a MOOC due to the current interest in the topic.

The lecture covers the function of these devices – concentrating mainly on high temperature solid oxide cells (SOC) and their reversible operation (rSOC). Due to the importance of high temperature (co-)electrolysis in synthetic fuel production, power to gas technology is already introduced here (although more is covered in the following module C3).

Fuel Cell Systems (2 lessons = 2 x 50 minutes)

This lecture gives a basic introduction to components in fuel cell systems, differences between low and high temperature systems, and system efficiency:

- general system issues: efficiency, parasitic losses, internal heat or water recycling,

- gas supply (air and fuel),

- cooling,

- water and heat management,

- fuel processing and reforming, anode gas recycling,

- components: afterburner, blowers, heat exchangers,

- electrical grid connection (incl. DC/AC conversion),

- system packaging.

Fuel Cell Applications (2 lessons = 2 x 50 minutes)

This lecture introduces the various applications of fuel cells. Students are given guidance and insight useful for the coursework. Comparisons are drawn with internal combustion engines and batteries and the merits drawbacks of the competing concepts discussed.

Topics covered are

- requirements to performance and lifetime;

- fuel cell electric vehicles;

- auxiliary power units;

- power generation;

- uninterruptible power supply;

- CHP and Combined Cooling Heating and Power (CCHP), polygeneration;

- portable and luggable applications.

Fuels for Fuel Cells (2 lessons = 2 x 50 minutes)

Due to the multiple interactions between fuel cell systems, applications, and fuel supply, it has been decided to cover this area in one lecture in module C2. Again, students will receive important input they can use in the coursework.

Fuel covered of course include hydrogen, but also natural gas, methane, biogas, ammonia, methanol, ethanol, carbon and hydrocarbons in general, and other hydrogen-containing compounds, including borates and LOHCs.

Degradation and Lifetime Issues (2 lessons = 2 x 50 minutes)

This lecture introduces the basic concepts of limited lifetime with fuel cells. It discusses the requirements for consumer products and the physico-chemical phenomena that lead to the continuous reduction in performance:

- requirements for lifetime of consumer products: portable, mobile, stationary,

- degradation and causes of degradation in PEFC/DMFC,

- degradation and causes of degradation in SOFC,

- degradation and causes of degradation in MCFC,

- concepts of lifetime testing.

Market Introduction and Market Development (2 lessons = 2 x 50 minutes)

… introduces the problems faced by disruptive technologies when accessing or opening markets. As a new product, fuel cells tend to be expensive and thus face a basic problem of market adoption, albeit being an ‘environmentally benign’ technology that benefits society.

- disruptive technologies,

- the case of battery electric vehicles: Tesla (how did they do it?),

- benefits of fuel cell electric vehicles, how can these be exploited?

- the concept of ‘added value’ and ‘external costing’ (total societal cost),

- specific fuel cell markets, niche markets.

Outlook & Future Trends (2 lessons = 2 x 50 minutes)

This lecture discusses a number of topics from current research and the pathway forward to fuel cell technology adoption.

- specific research challenges: degradation, freeze start,

- lifetime issues and accelerated testing,

- materials performance and lifetime trade-offs,

- success stories from various companies: Bloom, Smart Fuel Cells,

- governmental programmes: Japan, EU.

2.2.2 Learning outcomes

After absolving the module the students should be able to:

- Present and criticise the potential, benefits, boundary conditions, and prospects of employing fuel cell technology today and in future markets;
- Describe the Physics, Chemistry and Engineering of fuel cell technologies and be able to apply this knowledge to moderately complex problems;
- Be able to choose appropriate technology when faced with a moderately complex engineering design task;
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

2.3 C3 - Hydrogen (production, storage, handling), fuels (P2G, P2X) (UPB), electrolysers (UCTP, Grenoble INP)

2.3.1 Module content

The content for the mandatory module “Hydrogen (production, storage, handling), fuels (P2G, P2X) electrolysers” is developed by UPB.

This module is delivered face-to-face or fully online as a block-release and focuses on the fundamentals of hydrogen production and utilisation. This module combines a variety of disciplines from area of hydrogen production, storage, transport or delivery.

The hydrogen (production, storage, handling), fuels (P2G, P2X) module aims to introduce hydrogen (technologies) production and fuels to students and provide them with the basic science behind the processes involved. Hydrogen is an important raw material for the chemical, petrochemical or agrochemical industry, with the big chances to become an energy carrier alongside electricity in the near future. This will be useful for both students progressing into the area of hydrogen production and its utilisation in energy generation/storage, as well as those aiming at getting involved in the FHC field itself, for instance by taking up a PhD in the Doctoral Training School for FCH.

A well-thought-out and reinforced programme for the use of hydrogen for multiple purposes will have to consider the potential of all sources of energy and raw materials for its production. Here are included: fossil sources with carbon sequestration (coal and natural gas), renewable energy sources (solar, wind, and hydroelectric), biological methods (biomass and biological), and, but not at the end, the nuclear energy.

The module consists of 14 lectures:

1. Hydrogen, introduction;
2. Fossil hydrogen production, part 1+2;
3. Hydrogen production by the electrolysis of water at normal temperature -part 1+2;
4. High temperature water electrolysis;
5. Hydrogen production using nuclear energy and thermo-chemical cycles;
6. Renewable hydrogen, non-electrolysis - part 1;
7. Renewable hydrogen, non-electrolysis and natural (geologic) hydrogen -part 2;
8. Separation and Purification of Hydrogen;
9. Hydrogen Storage;
10. On board storage;
11. Infrastructure, supply chain, transport, HRS;
12. Power to Gas.

Taking into account the discussions within the consortium and UPB working group, which focused primarily on the existing level of knowledge and also on the real needs of the future students, the initial name of the lectures and their volume in the course suffered some changes to the proposed form.

The material produced for this module was designed so that it has a high degree of reusability.

2.3.2 Learning outcomes

By the end of the module students should be able to:

- Present and criticise the methods, potential, benefits, and prospects of hydrogen production, storage and safety handling.
- Understand concepts that relate to Power to Gas and Power to X concepts.

- Describe the Physics, Chemistry and Engineering of hydrogen production and storage technologies and be able to apply this knowledge to moderately complex problems.
- Be able to choose appropriate technology when faced with a moderately complex engineering design task.
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

2.4 C4 - Fuel cell modelling tools (POLITO, Grenoble INP) and control (TUD)

2.4.1 Content development

The modelling material has been organised into 9 lectures with variable length depending on the topic and its contents. This sub-module has a duration of 22.5 hours. At the beginning of each presentation, the lecture outline, with the indication of the sub-sections composing the block, has been inserted to facilitate and enhance the material understanding.

- Introduction on modelling of fuel cell systems (1.5 hours). An overview of modelling techniques is briefly presented, emphasising the different scales for modelling: from molecular level to the whole plant/process scale. Multidisciplinary approach is underlined, as fuel cell modelling require a pure science background (material science, physics and chemistry) as well as an engineering one (transport phenomena, thermal and fluid dynamics).
- Thermodynamics and electrochemistry basic principles (2.5 hours). The lecture provides a brief introduction on the electrochemical cells classification according to the operating mode (galvanic or electrolytic) and to the ion transported (anionic or cationic). The basics of ionic conduction are briefly recalled, as well as the thermodynamics principles. Then, irreversible phenomena and their effect on the fuel cell polarisation (i.e., in terms of voltage and current) are shortly introduced, as well as the heat balance of a cell.
- Transport phenomena (2 hours). The presentation contains a brief introduction to the modelling of transport processes occurring at anode and cathode side (that will be more deeply analysed within the 'Advanced modelling' optional module). The attention is focused on the multiscale approach. FC systems can be considered as non-linear dynamic systems with multiple inputs and outputs in which mass, momentum, energy and charge transfer take place together with chemical and catalytic reactions. The goal of modeling is to develop mathematical tools capable of simulating the response of the system in terms of pressure, temperature, fluid composition and charge species distribution within both time and spatial domains.
- Electrochemical modelling (2.5 hours). The main purpose of this lecture is to provide the tools in order to establish a relationship between irreversible phenomena and polarisation losses (i.e., overpotentials). The goal of an electrochemical FC model is to provide a mathematical formulation of the relation between electrical variables of the fuel cell (i.e., current and voltage) and thermo-fluidic and chemical variables (i.e., temperature and species partial pressures). The lecture provides the formulation of reversible potential through the Nernst Equation. Then, each type of overvoltage (activation, ohmic and concentration) is presented with the corresponding equation
- PEMFC modelling (4 hours): the different modeling approaches are adapted to PEMFC issues. Firstly, stationary models are described. 0D model is used for polarisation curve calculation to predict PEMFC efficiency or to fit experimental data for diagnosis. Water management is discussed with a 1D model included water transport in membrane. For dynamic simulation, usual equivalent circuit uses for PEMFC is introduced.
- SOFCs modelling: multidimensional approach (1 hour). The modeling approach presented in this section provides a mathematical description of the physical phenomena occurring in FCs from a macroscopic point of view. In the literature, macroscopic FC models have been developed from 0-D to 3-D depending on the model objectives. In this lecture, the attention is focused on O-D and 1-D models (2-

D and 3-D are discussed in a dedicated lecture within the 'Advanced modelling' module). 0-D models are typically used to simulate the polarisation of an FC and to analyse the cell performance with the variation of operating conditions. 1-D models are typically used to describe the evolution of thermo-electrochemical variables within the cell by considering one dominant geometrical dimension (generally the gas flow direction).

- SOFC stack and system modelling (5 hours). This lecture focuses on the modelling of high-temperature-based FC systems. The tools and techniques that are widely used to model the energy and electrochemical behaviour of SOFC systems are introduced. The attention will be focused on SOFC systems performance, on the comparison with other conventional power technologies and on tools for the preliminary design and optimisation. The detailed description of Balance of Plant (BoP) components is provided, as well as a methodology for plant design. Then, the energy analysis of SOFC system is described, starting from the reversible potential towards the energy model of the stack/system. Heat exchange network (HEN) design methodology is described for internal energy integration, improving the overall system efficiency. Finally, techniques for plant optimisation and techno-economic assessment are briefly explained.
- Exercises on SOFC (2 hours). Six (6) exercises on mass balances, energy balances, efficiency calculation, Nernst voltage, Air utilisation and power density are stepwise solved to make the student more confident with numerical results (and their order of magnitude) for SOFC cells/systems.
- Seminar on biogas-fed SOFC-based systems (2 hours). In this seminar a real example of a biogas-fed SOFC-based system, related to experience developed by Politecnico di Torino in the European project DEMOSOFC (funded by the Fuel Cells and Hydrogen 2 Joint Undertaking) is presented. DEMOSOFC is devoted to the design and installation of an SOFC plant that generates around 175 kW electric. The SOFC plant has been installed in a WWTP (Waste Water Treatment Plant) in the Turin area, and guarantees the supply of around 30% of the site electrical consumption, and almost 100% of the thermal requirement. The DEMOSOFC plant is the first example in Europe of high efficiency cogeneration plant with a medium size fuel cell fed by biogas.

2.4.2 Learning outcomes

From following this module students should be able to:

- Discuss the mathematical tools that are required to simulate the operation and performances of a fuel cell system, including an overview on the equations to model the fundamental physical phenomena occurring inside the active layers (electrodes and electrolyte) of the electrochemical cell.
- Explain methodological approaches that are required to design and simulate the performance of fuel cell or electrolyser systems.
- Understand the modes of operation of a fuel cell and the operating principle(s) of single components comprised in a fuel cell system.
- Display knowledge on how to perform energy systems analysis of fuel cell systems with a focus on stationary applications.

2.5 C5 - Characterisation methods (EPFL)

2.5.1 Module contents

The teaching of characterisation methods for describing the behaviour of fuel cells and water electrolysers covers the main aspects of construction and operation. The methods range from characterising constituent materials used to make components and single cells, to short stacks and finally through to full stacks and systems. The need to address lifetime degradation and operational changes is achieved by treating characterisation before, during and after operation, in other words both spatial and temporal considerations are explained.

This module comprises of 12 lectures. Each lecture is in PowerPoint format with additional videos and pre-recorded material where appropriate. Each lecture will have associated exercises and lab sessions. The total duration is 22.5 hours

The module starts with an overview lecture which outlines the following sub-topics-

- Electrochemical characterisation methods
- Applications to fuel cells and water electrolysis
- Materials, components, cells, stack and balance of plant
- Characterisation of materials used to make components
- Characterisation of components before use for quality control
- Characterisation of single cells during and after operation
- Characterisation of stacks and short stacks during and after operation
- Characterisation of balance of plant

The lectures are arranged chronologically as follows-

1. General Introduction to characterisation methods
2. Electrochemical methods for cell testing during operation- including determination of IV characteristics and EIS responses
3. Stack electrochemical characterisation during operation – including IV characteristics, EIS resposes and power performace characteristics
4. Fuel cell single cell characterisation and electrolysis characterisation, including half-cell measurements
5. Stack degradation characterisation during operation
6. Components, cell and stack degradation post-operation characterisation
7. Short stack characterisation
8. Quality control on components and cells, pre-operation
9. Quality control on stack and systems, pre-operation and during operation
10. Flow fields and current collection
11. Characterisation of components, pre- and during operation
12. Characterisation of materials used to make cells and stacks

2.5.2 Learning outcomes

The outcomes of the module will provide understanding and competence in the following areas-

- Inspect and appraise the performance of fuel cells in terms of stability, power output, longevity;
- Plan and design experimental procedures to critically evaluate the operation of fuel cells, catalyst utilisation, electrochemically active catalyst surface area and poisoning;

- Assess and evaluate the different electrochemical concepts including cyclic voltammetry, electrochemical impedance spectroscopy, chronoamperometry to study fuel cells components;
- Compare, differentiate and analyse different material characterisation techniques;
- Evaluate different material properties and requirements (morphology, conductivity, water retention etc) for electrocatalysts, catalyst supports, conducting membranes and other fuel cell components by combining electrochemical and material characterisation.

2.6 C6 - (Remote) Laboratory Training (POLITO)

2.6.1 Module delivery

The Labs module is organised in two sub-modules: A and B. The sub-module A is offered locally by each single hosting university with a physical laboratory based on a specific hydrogen/fuel cell topic (locally selected); the sub-module B is a a module dedicated to fuel cells characterisation through a physical laboratory for remote SOFC testing provided by POLITO to all the Consortium. This laboratory is physically located in POLITO and allows to remotely control the experiments.

Each sub-module is composed by a part of lectures introducing the topic before the part of laboratory. The sub-module A offered by POLITO provides a background to the students in hydrogen generation by solar-driven chemical looping water splitting, the sub-module B in SOFC testing. The module A introduces materials, reaction kinetics, reactors and cycle configurations for the chemical looping water splitting technology, with a lecture devoted to laboratory experiments. A total of 5 lectures (10 h) is provided in the sub-module A and 1 physical laboratory (2 h). The sub-module B introduces basic principles for electrodes, cells, stacks and components testing, with DC and AC characterisation techniques, with a seminar on the effect of contaminants in SOFC and a remotely controlled experiment on a SOFC cell. A total of 6 lectures (10 h) is provided in sub-module B with 2 remote laboratory lectures (1 h tutorial, 3 h experiment).

2.6.2 Sub-Module A: Hydrogen generation through chemical looping

- <u>Introduction to chemical looping and materials for water splitting cycles and simple configurations of chemical looping plants</u> (3 hr). This lecture provides an introduction to chemical looping water splitting, explaining the basic thermodynamics and briefly presenting the main oxygen carrier materials adopted in chemical looping cycles. Plant configurations are presented focusing on efficiency and environmental performance. System analysis of chemical looping water and carbon dioxide splitting plants is presented. The main configurations of laboratory plants for chemical looping studies are also presented.
- <u>Introduction to solar reactors for chemical looping water splitting</u> (1.5 hr). This lecture focuses on chemical looping solar reactors, introducing different reactor configurations and providing a complete overview on the developed and modeled reactors.
- <u>Reaction kinetics: introduction and simple kinetic models for experimental data fitting</u> (2.5 hr). This lecture focuses on the kinetics of reduction and oxidation reactions in chemical looping two-steps cycles. An analytical model, Arrhenius-based, is presented with reference to the most common oxygen carrier material in the literature (Ceria). Simple data fitting techniques applied to kinetic models are also presented.
- <u>Introduction to gas analysis techniques and hydrogen detection technologies</u> (2 hr). This lecture focuses on hydrogen detection techniques. A general overview is provided, with a specific focus on mass spectroscopy related to hydrogen measure in chemical looping experiments.
- <u>Laboratory: measure of hydrogen generation peak from water splitting on metal oxides, data analysis and basic kinetics extrapolation</u> (2 hr). This is the physical laboratory of the sub-module A, provided by POLITO in its laboratory facilities. Students will perform a basic water splitting experiment on a pre-prepared oxygen carrier sample in the lab, collecting data from gas analysis and extrapolating basic

kinetics from the measures, applying the knowledge acquired in the previous lectures.

- Chemical looping: outlook and research trends (1 hr). The final lecture is on the perspectives of chemical looping water splitting, summarising the main trends of research and the ongoing projects on the topic.

2.6.3 Sub-Module A: Electrochemistry in practice, electrochemistry cell (Grenoble-INP)

Grenoble-INP benefits from a platform of practical work dedicated to electrochemistry. It allows practical work to be carried out on the characterisation of materials for electrochemistry, corrosion studies and complete cell tests. The module is a complement to mandatory module as Introduction to fuel cells or thermodynamics, electrochemistry, chemistry. Labworks takes typically 4 hours and can be included in CPD.

Exemple of labwork and experimental project :

- Labwork of Materials Science, Processes and Electrochemistry
  - Charge/discharge of batteries
  - Corrosion
  - Electrochemical kinetics of coper deposition
- Labwork of Electrochemical systems
  - Electrode potential and potentisotatic regulation
  - Junction potentials
  - Diffusion and migration phenomena
  - Characteristics of non-stationary electrochemical methods
- Labwork of corrosion
  - Influence of a protective film on corrosion
  - Pitting corrosion
  - Galvanic coupling
- Experimental projects in electrochemistry and chemical engineering
  - Breathing PEFC
  - Electrokinetic study of ORR with various catalyst
  - PEFC stack characterisation: influence of operating condition (in the process of assembly)
  - PEM and alkaline electrolysis

2.6.4 Sub-Module B: SOFC testing

- Introduction to fuel cell testing: basic principles for electrodes, cells and stacks testing (2 hr). This lecture provides an introduction to the electrochemical testing and characterisation of electrodes, cells, and short stacks, with a specific focus on SOFCs. The measurement of potential difference, temperature and the electrode geometries and test set up configurations are presented. The choice of sealing, contacting, operating conditions are also addressed.
- DC polarisation techniques for fuel cell testing and ASR extrapolation (1 hr). After showing the basics of fuel cell testing in the previous lecture, the DC characterisation of cells is presented. This lecture shows the criteria followed for choosing the test conditions (air utilisation, fuel utilisation, etc.) for polarisation (current voltage) tests and how to derive area specific resistance (ASR) from cells polarization data.

- AC techniques: introduction to EIS principles and EIS data interpretation by equivalent circuits, DRT and ISGP methods (3 hr). This lecture focuses on AC characterisation techniques for electrodes and cells. The basics of impedance spectroscopy (EIS) are introduced and the equivalent circuit modelling of cells for EIS interpretation is explained. An overview on advanced EIS analysis techniques, such as ADIS, DRT and ISGP is presented.
- SOFC components: testing of sealants and interconnects (1 hr). A brief overview on testing of cell and stack sealants and of interconnects is presented in this lecture. The lecture has a specific focus on measuring resistivity of SOFC glass-ceramic sealing materials.
- Tutorial on SOFC remote laboratory for polarisation experiments (1 hr). This lecture consists in a remote tutorial for the SOFC laboratory. A demo of the remotely controlled SOFC polarisation experiments will be made available for students to train before the remote lab.
- Laboratory for remote SOFC experiment: cell polarisation and data analysis (3 hr). The laboratory consists in a remote SOFC polarisation experiment. A test-rig put in operative conditions in POLITO laboratory is made available to students for remote control. The students will have the control a limited set of test variables in a safety range and will have a task to complete in the lab using the equipment remotely controlled. Students will have to decide autonomously the operation conditions to be set for the test in order to achieve the given task by applying the knowledge acquired in the previous lectures. Students will perform the DC characterisation and collect the data. By extrapolating the data, they have to calculate the set values required by the task and compile a short report by the end of the lecture.
- Seminar: impact of contaminants on SOFC performance, introduction to contaminants and interpretation of SOFCs characterisation in the presence of contaminants (2 hr). This seminar provides and introduction on the main contaminants of SOFC applications and of their impact on SOFC performance (cell and stack), with a particular reference to biogas contaminants (ie., sulfur, siloxanes). The contaminants measurement techniques from gas analysis to cell characterisation will be explained.
- SOFC testing: outlook and concluding remarks (1 hr). The final lecture summarises the status of SOFC testing, providing a brief overview also of state-of-the-art characterisation techniques not covered in the module, such as thermo-mechanical and structural techniques, to provide a complete view on testing of SOFC.

2.6.5 Learning outcomes

After having followed this module students should be able to

- Inspect and appraise the performance of fuel cells in terms of stability, power output, longevity.
- Plan and design experimental procedures to critically evaluate the operation of fuel cells, catalyst utilisation, electrochemically active catalyst surface area and poisoning.
- Assess and evaluate the different electrochemical concepts including cyclic voltammetry, electrochemical impedance spectroscopy, chronoamperometry to study fuel cells components.

2.7 C7 - Hydrogen safety (UU)

The content for the mandatory module “Principles of Hydrogen Safety” is developed by UU and forms the part of deliverable D2.2.

This module is delivered fully online or face-to-face as a block-release and focuses on the fundamentals of hydrogen safety science and engineering. This module combines a variety of disciplines in an engineering framework 'Principles of Hydrogen Safety' that includes but not limited to relevant RCS. Insight into these principles is developed to enable the student to understand the origin and phenomenology of hydrogen safety problems involving unscheduled releases and dispersion of expanded and under-expanded jets, ignition mechanisms, microflames, hydrogen jet fires and associated hazard distances, etc. The case studies are the part of the module to reinforce the best practice in hydrogen safety

2.7.1 Development of ‘remote lab’ concept

UU is planning to assist the project partner POLITO in development of “remote lab” by provision of interface to e-Laboratory of Hydrogen Safety developed within NET-Tools project. The e-Learning platform was established within European project NET-Tools where all tools for hydrogen safety engineering were gathered in one place called e-Laboratory. E-Laboratory is closely linked to the module “Principles of Hydrogen Safety” delivered at UU: the theoretical material and models given in lectures are realised in e-Laboratory as ready to use online engineering tools. A successful student should be able to solve real problems using e-Laboratory tools and then present correct results as a part of the module assessment (quizzes and courseworks). E-Laboratory was proposed to be used for the MSc course being developed within TeacHy, its interface and description will form UU contribution.

2.7.2 Development of the module materials

This module is delivered fully online or face-to-face as a block-release and focuses on the fundamentals of hydrogen safety science and engineering. This module combines a variety of topics relevant to the safety engineering framework including relevant RCS. The module enables a student to understand the phenomena associated with modern hydrogen technologies and scientific foundation behind relevant hydrogen safety engineering methods and models. The considered phenomena include unscheduled releases and dispersion of expanded and under-expanded jets, ignition mechanisms, microflames, hydrogen jet fires and associated hazard distances, etc. The case studies are the part of the module to reinforce the best practice in hydrogen safety.

The module consists of 12 lectures:

1. Introduction to hydrogen safety
2. Hydrogen properties and hazards, comparison with other fuels
3. Regulations, Codes and Standards (RCS) and hydrogen safety engineering
4. Unignited releases
5. Ignition of hydrogen mixtures
6. Microflames
7. Jet fires - Part 1
8. Jet fires - Part 2
9. Hydrogen permeation
10. Compatibility of metallic materials with hydrogen

11. Materials for hydrogen technologies
12. Case studies

Each lecture is concluded by an online self-assessment quiz. The online self-assessment quizzes are formative assessment but do not count towards the module mark. Successful completion of the quiz of a lecture enables access to a subsequent lecture.

The module assessment consists of two pieces of coursework - one in the first half, and one in the second half of the semester. Each piece of coursework contributes 50% to the overall module mark. Each piece of the coursework contains mix of problem-based solutions requiring answer as a numerical value and qualitative questions requiring essay-style answer. The coursework may incorporate tests of factual knowledge, problem solving.

2.7.3 Learning outcomes

After completion of the module the successful students will be able to:

1. Demonstrate knowledge related to hydrogen properties and hazards and ability to apply this knowledge to hydrogen safety engineering design, including compliance with regulations, codes and standards
2. Evaluate requirements for safety provisions by taking into consideration knowledge on hydrogen releases, ignition, jet fires and material properties
3. Illustrate mastery in analysing complex hydrogen safety problems both systematically and creatively, by integrating fundamental knowledge and engineering approaches from a variety of disciplines
4. Apply self-direction and originality in tackling and solving hydrogen safety problems at a professional or equivalent level.

3 Optional modules

3.1 O1 - Environmental analysis, life cycle analysis (UBHAM)

3.1.1 Module content development

The Environmental Life Cycle Analysis (LCA) module aims to introduce environmental analysis methods to the students. It is loosely based on the ISO 14040 (and following) standard definitions and inventory processes of all environmental effects and arbitrary (human) activity, from cradle to grave. The environmental life cycle analysis considers the overall ecological balances that fuel cell and hydrogen systems create. Topics included will cover energy use and energy efficiency, fossil energy use, and finally full environmental inventory and impact analysis.

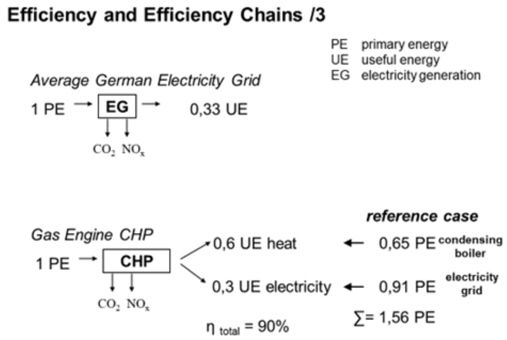
The module includes 12 lectures (double lessons, 2 x 50 minutes) on the following topics:

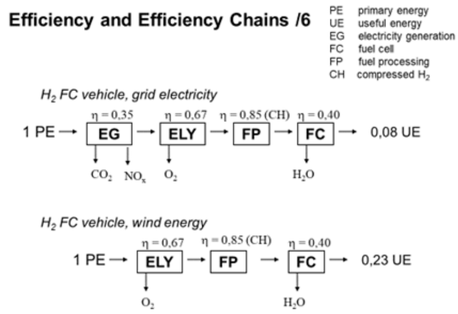
1. Introduction - What do we want to analyse?
2. Performance indicators: energy efficiency;
3. Cumulative energy, energy payback;
4. Types of environmental impact;
5. Types of environmental impact assessment;
6. LCA standards, software and databases;
7. LCA procedure;
8. Case study: bus transport;
9. Aggregating and weighting LCA results;
10. Pricing environmental impact: Externalities;
11. Case study: residential heating and district heating;
12. Case study: electricity generation.

The Environmental life cycle analysis considers the overall ecological balances that fuel cell and hydrogen systems create, which include the following:

1. Energy Conversion Chains,
2. Efficiency chains, and the full
3. Life Cycle Analysis (LCA).

The energy conversion chains consider the energy used in the production, from primary energy source to energy delivered to the customer. The analysis follows the trace of the conversion process and uses efficiency values to map the loss of energy along the process chain. Two examples are shown here for CHP and electric vehicles.





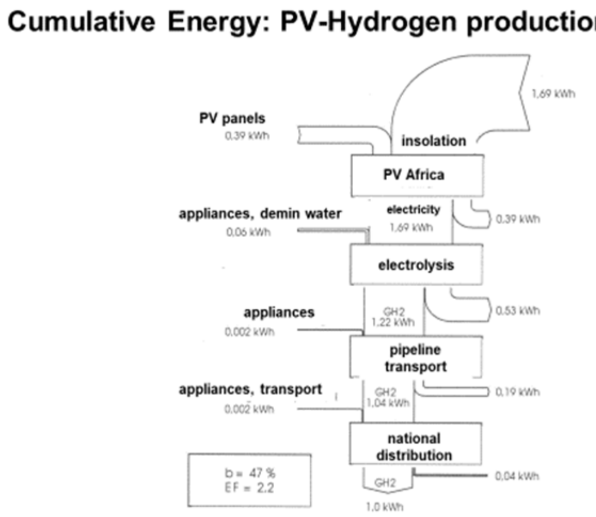
Cumulative Energy is given by

b = total chain energy efficiency = (primary) energy output / (end) energy input

and also includes any energy input that was spent on manufacturing or building any of the conversion equipment. The *energy harvest factor* then goes on to calculate the 'efficiency' with regard to fossil energy sources, i.e. determining the leverage of renewable energy input on overall energy delivery.

Cumulative energy also takes the operating energy into account, which includes:
- energy consumption of actual components/process steps
- maintenance (O&M)
- transportation energy for energy carriers
-installation energy:
- energy in building materials

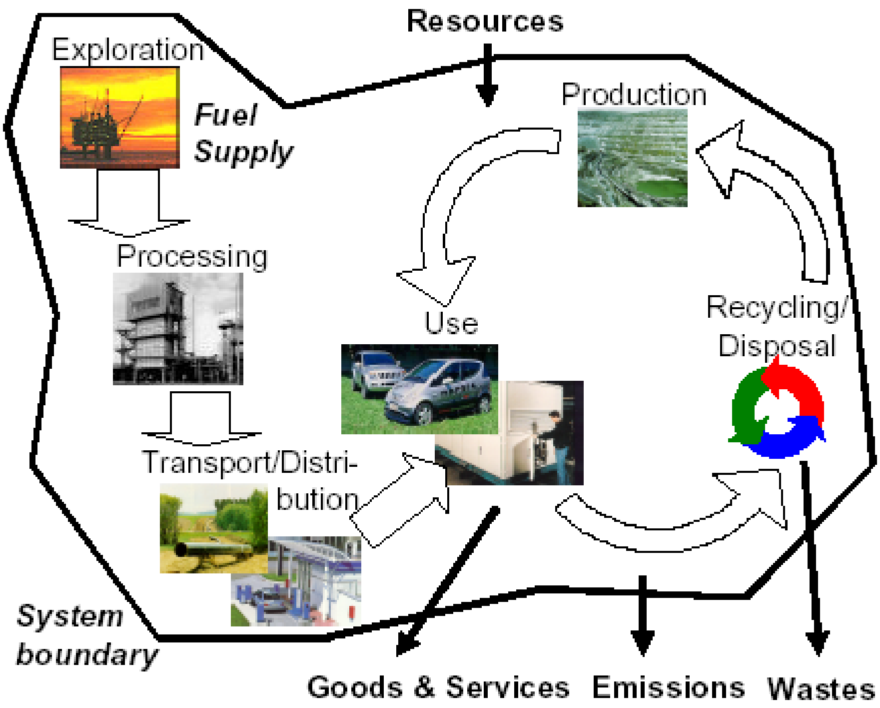
An example diagram is shown below for a PV-to-hydrogen conversion chain, using soalr energy in the North of Africa.



The LCA, in contrast, extends analysis to a set of 20 parameters, including

- Global warming
- Ozone depletion
- Acidification of soil and water
- Eutrophication
- Photochemical ozone creation
- Depletion of abiotic resources – elements
- Depletion of abiotic resources – fossil fuels

in the whole process life cycle from raw materials extraction to waste disposal as shown in the graph below.



3.1.2 Learning outcomes

After having followed this module students should be able to

- calculate conversion chain efficiencies and cumulative energy for moderately complex systems;
- explain the differences and communalities between global and local emissions;
- discuss issues and approaches of Life Cycle Inventories;
- explain and sketch out the process of Life Cycle Analysis;
- explain and discuss environmental costing approaches.

3.2 O2 - Low temperature fuel cells (materials, stacks, thermodynamics, electrochemistry, chemistry) (Grenoble INP, UCTP, DTU)

3.2.1 Module content

The optional module will cover LT-FCs, their science, materials, construction issues and applications (stationary and mobility). This module deepens the knowledge from previous mandatory modules. Therefore some clarification of general statements with specific focus to low temperature fuel cell was included in the module. The learning materials have been adapted from HYCHAIN project materials provided by Grenoble INP. 5 new lectures were created to cover all issues of LT-FC. The new lectures created at UCTP include Thermodynamics Fundamentals with focus on LT FC, ion exchange membranes, their synthesis and characterisation, alkaline fuel cells, bipolar plate design, flow distribution and modelling.

Module overview:

The module consists of 11 double-lesson (2 hours = 2 x 50 minutes) individual lectures focused on specific topics related to LT-FCs:

- electrochemistry/thermodynamics: this is a quick reminder of the concepts and how to apply it to the LTFC
- design and components of LT-FC: this lesson explain the different step to choose and design the right configuration of LT-FC. All stack components are introduced.
- Materials for MEA (Membrane Electrode Assembly): catalyst, GDE, separator, membrane preparation and characterisation
- Stack assembly: bipolar plates and channel design, cooling issues
- Special attention is paid to the separators used in PEM FC and also AFC. Bipolar Plate design synthesis and an overview of testing methods is given in two lectures (4h).
- LT-FC degradation issues: PEMFC durability (4h): the focus of this part is on aging, catalyst behaviour and the effect of the operating conditions on the durability (start/stop, starvation, humidity etc.).
- Alkaline fuel cells (AFC) are discussed as well (2h)

3.2.2 Learning outcomes

By the end of the module students should be able to

- Present and criticise the potential, benefits, boundary conditions, and prospects of employing LT-FC technology today and in future markets;
- Describe the theoretical basis of LT-FC with respect to the electrochemistry and thermodynamics and be able to apply this knowledge to moderately complex problems;
- Be able to choose appropriate technology when faced with a moderately complex engineering design task;
- Select appropriate materials for LT-FC designs and define crucial properties;
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

3.3 O3 - High temperature fuel cells (materials, stacks, thermodynamics, electrochemistry, chemistry) (TUD, KPI)

3.3.1 Module content

The module on high temperature fuel cells focuses on the two main types – SOFC and MCFC. In each case the materials used make the cells are discussed in terms of their chemical properties, their function and performance. The thermodynamics and electrochemistry of the single cell and stacks are then described with examples of iV-performance characterisation, degradation phenomena and electrical efficiency. In the case of SOFC the reverse operation as SOEC is also discussed as this technology is emerging as a major source of hydrogen production. In SOEC mode particular attention is given to operation under thermos-neutral conditions – a feature that set this technology apart from conversional low temperature electrolytic cells.

The lectures will cover the following topics:

- Thermodynamics
- Cell and stack design
- Electrode polarisation
- Fuels and fuel processing

3.3.2 Learning outcomes

By the end of the module students should be able to

- Present and criticise the potential, benefits, boundary conditions, and prospects of employing HT-FC technology today and in future markets;
- Describe the theoretical basis of HT-FC with respect to the electrochemistry and thermodynamics and be able to apply this knowledge to moderately complex problems;
- Be able to choose appropriate technology when faced with a moderately complex engineering design task;
- Select appropriate materials for HT-FC designs and define crucial properties;
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

3.4 O4 - Low temperature systems (DTU)

The module on low temperature systems is built-up of a number of lectures describing the overall system need for low temperature fuel cell systems as well as details of the components in the systems. Focus is on PEFC systems, but with a lecture covering the systems need for alkaline fuel cells (AFC) as well.

Lectures will be a presentation of the subject followed by a number of exercises to illustrate the main points of the lecture and engage the students.

The modules consist of 10 lectures and has an overall length of approx. 20 hours.

3.4.1 Overview of lectures

<u>System component and balance of plant</u> (1 lecture approx. 120 min)

A description and overview of the different components need for the operation of low temperature systems. Overview over different operating modes and requirements for the system. List of mandatory as well as optional modules and their main functions, leading up to details description in the following lectures.

<u>Hydrogen supply (1 lecture approx. 120 min)</u>

The lecture covers the system components needed for supply of fuel (hydrogen), topics covered are the following: Hydrogen storage options (primarily pressurisation), pressure regulation, purity of fuel, impurities, both on fuel, humidification, anode gas recycling, fuel utilisation.

<u>Hydrocarbon fuel processors for PEFC systems (1 lecture approx. 120 min)</u>

The lecture covers the use of hydrocarbon sources for the hydrogen supply, including the basic reforming processes and reactions, specifically methanol, methane and propane reforming, gas processing and clean-up, the water gas shift reaction, fine cleaning as well as purity requirements.

<u>Heat management (1 lecture, approx. 120 min)</u>

Lecture covering how to cool as well as heat up LT PEM systems, as well as heat integration with other components (reformers etc.) Topics covered includes cooling media (air, cathode air, liquids), useful heat extraction, heat recycling, heat exchangers, afterburners and start up.

<u>Oxidants – Oxygen and air systems (1 lecture, approx. 120 min)</u>

The lecture covers how to supply oxidant to the fuel cell systems, topics include: Air or oxygen supply, blowers and compressors, pressurised systems, passive air supply, water and heat management, oxidant clean up and impurity tolerance.

<u>Electrical Subsystem (1 lecture, approx. 60 min)</u>

Overview of needed electrical subsystems, including DC/DC converters, DC/AC converters, connection to DC systems (e.g. vehicles, UPS, APU), connection to AC systems (e.g. grid, UPS etc.).

<u>System degradation mechanisms (1 lecture, approx. 120 min)</u>

The lecture covers common system component degradation mechanisms such as cell deactivation, catalyst poisoning (both anode and cathode), carbon corrosion, bipolar plate corrosion, effect of operating modes (cycling, constant current etc.), thermal cycling, rapid start-up, standby, freezing, vibration.

<u>Designing systems (1 lecture, approx. 180 min)</u>

The lecture covers how to design a LT PEM FC system, including design targets, system sizing and layout, system efficiency, Sankey diagrams and system components losses, system integration, simplification vs. high efficiency: mobile and stationary designs, system optimisation as well as common drawbacks of different design routes.

Optimisation of the system towards durability targets are also covered.

<u>Other low temperature systems (2 lectures, approx. 240 min)</u>

An overview of other low temperature fuel cells systems, and how they differ from the most common LT PEM FC system. There is a lot of common components between the different systems, but simplification as well as addition need to be made on the different system components.

The following low temperature systems will be covered: High temperature PEM FC, Direct methanol Fuel Cells (and other internal reforming systems) and alkaline fuel cells.

3.4.2 Learning outcomes

By the end of the engagement with this module students should be able to

- Define, present and explain the structure, main components of an LT-FC system;
- Describe the interaction and interdependencies of system architecture and specific application;
- Be able to calculate fuel and energy flows in the system and estimate system efficiency;
- Select appropriate fuels and fuel processing for the LT-FC design.

3.5 O5 - High temperature systems (UBHAM)

3.5.1 Module content

This course module on high temperature systems focuses on the balance of plant for SOFC and SOEC systems up to 20 KW, primarily for stationary applications. Examples are taken from stacks developed in Europe by major FC companies such as Solid Power and Sunfire. The course is split between modelling methods and physical BOP designs. Modelling tools such as COMSOL, MATLAB and Simulink are used to teach the basics of heat transfer and optimisation. Practical CHP examples such as home and office installations are considered including the installation of BlueGen systems for suppling domestic power and heating. The example of local grid will be explored, looking at battery-FC combinations for peak shaving and load balancing.

The use of biogas to fuel the SOFC will be studied with case histories taken from the farming community and local renovation plants. The quality of biogas and the means to store and purify will covered in the lectures.

Economic aspects of plant and installation costs and return on investments will also be included in the module.

In the case of SOEC, the production of hydrogen under thermoneutral conditions will be explored and the optimisation steps needed to ensure that this mode of operation is stable. Compression and hydrogen storage will also be studied to complete the BOP for steam electrolysis installations. The method and benefits of co-electrolysis of CO_2 and steam will also be explored and compared with normal steam electrolysis.

The course consists of 12 lectures in total with practical lab classes on benchtop setups and modelling exercises.

One of the major learning outcomes is that enough knowledge is gained to train SOFC installation engineers.

Students will be expected to choose a project title and write a report for grading assessment.

3.5.2 Learning outcomes

By the end of this module students should be able to

- Define, present and explain the structure, main components of an HT-FC system;
- Describe the interaction and interdependencies of system architecture and specific application;
- Be able to calculate fuel and energy flows in the system and estimate system efficiency;
- Select appropriate fuels and fuel processing for the HT-FC design.

3.6 O6 - Advanced characterisation (EPFL)

3.6.1 Module development

This module focuses on specialised analytical methods that can be used to characterise fuel cells electrolysers and stacks both before and after us. The methods are complementary to those described in the main module on characterisation and so knowledge of this first model is a pre-requisite to follow this advanced course. The course is broadly divided into the following subject topics-

1.1 Materials Characterisation

The advanced methods include the following-

1.1.1 Diffraction methods (X-ray diffraction, neutron powder diffraction, transmission electron microscopy) to characterise the phase composition and real bulk structure of materials

1.1.2 Scanning electron microscopy with EDX and elemental mapping: characterisation of morphology, chemical and phase composition of surfaces and interfaces (cross-sections)

1.1.3 Spectroscopic methods (EXAFS, XANES, MASNMR, FTIRS, Raman, UV- Vis, Mössbauer spectroscopy) to characterise the local structure of materials (coordination polyhedra, charge of cations)

1.1.4 Characterisation of the surface composition, chemical state of elements and metal-oxygen bonding strength by XPS and SIMS

1.2 Cell and Stack Characterisation

Advances techniques will include degradation analysis by EIS spectroscopy, and the novel technique of DRT and other methods based on harmonic analysis. Post-operational analysis by X-ray tomography and neutron scattering methods.

1.3 *Characterisation of Transport Properties*

This will be subdivided into the following:

1.3.1 **Conductivity measurements** using 4-wire methods inducing Van der Pauw

1.3.2 **Oxygen mobility** in the bulk (D*) and reactivity of surface sites (k_{exch}) by oxygen isotope hetero-exchange using techniques of Isotope Exchange Profiling SIMS, exchange in static reactor, exchange in the flow reactor (SSITKA), weight and conductivity transients (D_{chem} and k_{chem}); theory, methods and case studies.

3.6.2 Learning outcomes

This module will allow students to

- Understand and explain advanced chemical and physical characterisation methods;
- Discuss differences between and strengths of the main analysis techniques;
- Choose appropriate characterisation techniques for complex analysis problems.

3.7 O7 - High temperature chemistry for SOFCs/SOECs (TUD, KPI)

3.7.1 Module content

This module is an alternative version to O3 - High temperature fuel cells (materials, stacks, thermodynamics, electrochemistry, chemistry) with a stronger emphasis on electrochemistry, materials and manufacturing. Since both are optional modules, students are left with a choice of which module to take, though they are mutually exclusive, indicating that no student can book both modules.

The module has been developed by KPI based on a module already taught at the university. The material is organised according to the following lectures (one 'hour' corresponding to 45 to 50 minutes of traditional lecture time):

- Introduction in SOFC technology (2 hours). In the lecture, the phenomenon of ionic conductivity and the history of solid electrolytes are considered. Some properties of zirconia materials are listed, and the principle of dopant in order to choose structure stabilisers creating maximal number of oxygen vacancies is presented. The dependence of ionic conductivity on structure of electrolyte ceramics, and the test temperature are considered. Few samples of SOFC structures are given. At the end of lection, some requirements of SOFC electrolyte are listed.
- Zirconia powders and their electrolytes (2 hours). Zirconia is the main substance of the whole solid oxide fuel cell. It is not only the electrolyte material. It is added typically into both electrodes (anode and cathode) for spreading the reaction site deeper into them and adjusting thermal expansion coefficient compatibility with electrolyte material. Thus, it is important to understand the relationship between the characteristics of zirconia powder and obtained ceramic, it structures and properties. Three types of zirconia powder with the same chemical composition, but with different powder characteristics (i.e. particle size, specific surface, agglomeration, etc.) were used for preparation of ceramics. Structure, conductivity and mechanical strength of ceramics from different powders were compared.
- Anode component of solid oxide fuel cell, trends in its development (2 hours). In the first part of the lection the solid oxide fuel cell operation principle is briefly considered. After that, the basic geometries and configurations of SOFC are presented. Since the SOFC based on anode support is the most common used configuration, an overview of anode component is carried out. This review includes such the questions: anode requirements, traditional material of anode and its imperfections, alternative anode materials, and the three phase boundaries of anode material. Based on these questions the second part of lecture is devoted to the composition of the traditional nickel-zirconia anode. In this section the detailed overviews on each of anode component phases (nickel, zirconia and porosity) are presented. The third part of lecture is dedicated to trends in anode development. Bi-layered and gradient anode structures are considered. Then, the methods of nickel-zirconia composite preparation and the fabrication processes of anode are given.
- SOFC Cathodes (2 hours). The short explanation of SOFC operation principle is given. After that, the cathode requirements and features of cathode reaction are considered in detail. Cathode material should possess the oxygen ion conductivity; it is necessary to understand this process. Furthermore, electronic conductivity is also important requirement for cathode material. Thus, cathode material should demonstrate both ionic and electronic conductivity. Generally, materials that have mixed ionic and electronic conductivity (MIEC) are materials with perovskite

structure. Typical cathode materials and some their properties are listed. The problems associated with cathode degradation are considered. At the end of lecture some manufacture technology of cathode is listed.

- Materials for SOFC Interconnect (2 hours). The functions of interconnect are listed. Based on these functions the interconnect requirements are considered. FC interconnect materials can be grouped into two main categories: ceramics and metals (which includes coatings). Advantages and disadvantages of typical ceramic interconnect material ($LaCrO_3$) are presented. Metallic interconnect materials include Cr based alloys, Ni-Fe based superalloys, Fe-Cr based alloys and austenitic and ferritic stainless steels. Composition and properties of metallic interconnects are considered. After that, the tendency of using interconnects coatings is explained. Requirements and types of these coatings, and the methods of their manufacturing are given.
- Impedance spectroscopy (2 hours). Impedance spectroscopy (IS) is non-destructive method for characterisation the microstructure of heterogeneous systems. In the first part of the lecture, fundamentals of IS, fields and features of its application are considered. The advantages and disadvantages of IS are listed. Physical principles with mathematical background of IS, and examples of some electrical schemes were given. In the end of first part an exercise accompanied with impedance spectroscopy is presented. Second part of the lecture is dedicated to impedance measurements systems, the difference between them and principles of data analysis. Then, the examples of IS using in material characterisation is considered. Impedance spectroscopy can be used for characterisation of SOFC electrolyte structure, or even whole fuel cell (interface between components etc.). At the end of the lecture, some results of positive application of the IS method are presented.
- Electrode polarisation (2 hours). The first part of the lecture is dedicated to analysis of overall fuel cell performance. The actual performance of SOFC is differencing from theoretical one. There are a number of polarisations that impact on the performance: activation, Ohmic and concentration. The reasons and determination of these polarisations are considered. Then, the ways minimising fuel cell polarisation contributions are given. In the second part of the lecture, the anode polarisation is reviewed. In the section, the influence of anode composition, particle size and distribution of phases (nickel, zirconia and porosity) on electrode polarisation are considered in detail. The third part of the lecture is dedicated to cathode polarisation. The factors that influence on cathode polarisation are listed.
- SOFC testing (2 hours). In introduction of the lecture, the benefits of SOFC, their efficiency, comparison with traditional power generation systems and the operation principle of SOFC are briefly considered. The second part is dedicated to measurements of SOFC electrical properties. The current-voltage (I-V) characteristic of SOFC, typical tests conditions and basic stages of measuring of I-V curve are given. The last section of the lecture is focused on performance analysis of SOFC operation, and few examples of calculation of the SOFC efficiency are listed.
- Tape casting (2 hours). The main purpose of the lecture is to provide an understanding of the well-known high productive industrial method of film manufacturing known as tape casting. The principle of tape casting technique is explained, the advantages and disadvantages of this method are listed. Basic principles of colloidal stabilisation of tape casting slurries are shortly presented. Basics of slurry rheology and types of its flow character are represented and explained. The detailed description of relationships about the influence of slurry

composition and casting condition on tape properties are given. The post-processing techniques such as lamination (assembling a multilayer composite), annealing and sintering reviewed briefly. The last trends and achievements in tape casting technique are reviewed too.

3.7.2 Learning outcomes

By the end of the module the students will be able to:

- Understand fuel oxidation chemistry and electrochemistry in high temperature systems,
- Select suitable fuel processing methods, given the requirements,
- Understand the influence of contaminants on electrochemical processes and select suitable gas cleaning/processing routes,
- Be able to evaluate and select high temperature SOFC/SOEC systems and prepare an outline design.

3.8 O8 - Fuel cell electric vehicles (UBHAM)

3.8.1 Module content

This module explores the state-of-the-art in fuel cell vehicles and compare with the existing and expanding marked for electric vehicle. Emphasis will be given to cars, lorries, and buses but some examples of ships and other modes of transport will also be discussed. Worldwide deployment will be summarised, and some specific examples taken – such as fleet replacement in Norway and Switzerland.

Each of the vehicle manufacturers that are selling into the European market will be specifically discussed such as Toyota, Hyundai etc. This will include vehicle type, cost, range, power, lifetime, maintenance and recycling strategies. Hydrogen safety will also form a part of this module - storage tanks, their type of construction and their safety will be a specific topic.

The technical specification and fuel cell types will be explored along with basic design of the drive chain – types of electric motor, storage tanks, use of excess heat, cold starting (and parking) in sub -zero temperatures, regenerative braking and battery combinations for peak power control. The use of FCs as a range extender to existing vehicles will also be explored.

The module is also part of the Joint European Summer School on Fuel Cell, Electrolyser, and Battery Technologies (JESS, www.jess-summerschool.eu). It has been co-developed by the former head of Daimler Research, Prof Ferdinand Panik, and former head of department within Volkswagen Research, Prof Thomas von Unwerth, Toyota Europe training representative Vincent Mattelaer, and Prof John Jostins, member of the fuel cell vehicle development group spin-out companies at Coventry (MicroCab Ltd.). The module content will be published as a text book by Elsevier in 2020.

The module consists of 14 lectures of 60 to 90 minutes 'regular' timing (if delivered face-to-face). The following headlines describe the specific lecture content:

- Status of fuel cell vehicles - Passenger cars
- Status of fuel cell vehicles - Buses
- The 'elano' Concept of a Lightweight Vehicle
- Designing and building hybrid fuel cell vehicles
- Drive Train Components pt. 1/2/3
- Hybrid Vehicle Drive Trains
- Toyota Mirai product knowledge
- Vehicle Batteries
- several Exercises / Case studys
- System Analysis & LCA
- Safety in handling FCEV
- Outlook & Scenarios of market introduction

3.8.2 Learning outcomes

Students will be expected to learn the basics of FC vehicle layout and design and write a report for course assessment and grading. They will be able to

- Present and criticise the potential, benefits, boundary conditions, and prospects of employing fuel cell vehicles (FCEV) in decarbonising transport and their future market development.

- Describe the design basics of FCEV with respect to the main components, their performance and impacts on overall product and be able to apply this knowledge to moderately complex problems.
- Estimate environmental benefits of FCEV over competing technologies, both incumbent and future developments.
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

3.9 O9 - Politics, markets, regulation, codes and standards (UBHAM, ULB)

3.9.1 Module content development

This module will also be orientated towards training the target group of managers, local government officials and politicians in the state-of-the-art for hydrogen FC systems and infrastructure. Examples will be taken from existing and planned European projects. It is therefore a prime suspect for development into a MOOC available for free public access. The variation in regulations and standards worldwide will be explored and trading agreements. Specific examples will be taken for the introduction of FC vehicles in various countries– the impact on local communities, safety regulation and costs etc. Other examples will be taken from stationary applications such as local grid, domestic housing and offices etc.

The market opportunities, business models and political incentives will be explored along with governmental subsides and development project funding. Specific examples such as the replacement of diesel taxis and buses in London with fleets of hydrogen power vehicles will be explored, including the cost of the vehicles, cost of hydrogen filling stations and the associated safety and operational regulations.

Regulations, Codes and Standards for hydrogen and fuel cell technologies exist at national and international levels. In Europe, a database has been built under the FCH JU funded project HyLaw that ended in December 2018. This database will be maintained by Hydrogen Europe at least until December 2021.

20 lectures (double lessons, 2 x 50 minutes) are divided into the headlines

- European and national politics - introduction
- EU Directorate Generals ENER (Energy), MOVE (Transport), GROW (Growth), ENV (Environment), CLIMA (Climate), RTD (Research)
- FCH JU (EU), NOW (Germany)
- REACH
- U.S.A. DoE, NEDO (Japan), S.Korean govmt.
- Markets Europe & Worldwide
- Regulations, Codes and Standards - introduction
- Production, transport, handling of Hydrogen, including gas grid and storage
- Vehicles, HRS, H2 fuels; stationary applications
- HyLaw FCH JU project
- 5 Case studies

The course will initially illustrate the information available and how to navigate information in the public domain. The second part of the course consists of several case studies and a student project. For a given application in a selected country, the student will list all regulations, codes and standards that apply and will propose a scenario for the development of the application.

3.9.2 Learning outcomes

Having completed this module, students should be able to

- Present and criticise potential, benefits, boundary conditions, and prospects of employing fuel cell and hydrogen technology today and in future markets;
- Be able to identify the politics that will support the introduction of these new technologies in Europe and in the world;

- Be able to identify and find the regulations that have to be followed when developing such technology.

3.10 O10 - Energy system and storage (UPB)

3.10.1 Module content development

The content for this optional module has been developed by UPB. This module is delivered face-to-face or fully online as a block-release and focuses on the fundamentals of energy, energy storage and the role of hydrogen. This module combines a variety of disciplines from area of energy, energy production, storage, transport or delivery, renewable energy and the role of hydrogen in the energy system and energy storage.

The Energy system and storage module aims to introduce energy system and energy storage to students and provide them with the basic science behind the processes involved. This will be useful for both students progressing into the area of energy generation/storage, as well as those aiming at getting involved in the hydrogen energy field itself, for instance by taking up a PhD in the Doctoral Training School for FCH.

The domestically based and emission-free energy sources are high priorities for hydrogen further development. In the long-term perspectives, economics and a policy to support citizens' needs will determine the mix of energy sources that are implemented, and those technologies ultimately selected, that may differ from initially implemented, for long-term hydrogen deployment.

The module consists of 14 lectures:

- The actual energy system, introduction
- Fossil and nuclear energy production
- Renewable energy
- Energy vectors/carriers
- Hydrogen as energy vector/carrier, energetic properties of hydrogen
- Application to Fuel Cells and Electrolysers
- Energy storage and technologies
- Hydrogen for energy storage
- The hydrogen economy and sector-coupling
- Power to gas/x and NG network
- Hydrogen and fuel cells as UPS systems
- Hydrogen and fuel cells in energy supply of householders
- Energy and hydrogen corridors
- Aspects about safety, critical infrastructures and environmental impact of the energy system

Hydrogen has a very high gravimetric energy density; this phenomenon makes it an ideal fuel for various applications. The energy storage and industrial uses of the hydrogen are expected to grow significantly in the next years. This growth depends on the evolution of the energy system and of regulatory frameworks.

3.10.2 Learning outcomes

By the end of the module students should be able to:

- Present and criticise the methods, potential, benefits, and prospects of energy system and storage;
- Understanding concepts that relate to the concept of energy vectors;

- Describe the physics, chemistry and engineering of energy storage technologies and be able to apply this knowledge to moderately complex problems;
- Be able to choose appropriate technology when faced with a moderately complex engineering design task;
- Communicate information, concepts, problems and solutions to specialists and non-specialists.

3.11 O11 - Advanced modelling (POLITO, Grenoble INP)

3.11.1 Module content development

The advanced modelling material has been organised into 8 lectures with variable length depending on the topic and its contents. The module has a duration of about 25 hours. At the beginning of each presentation, the lecture outline, with the indication of the sub-sections composing the block, has been inserted to facilitate and enhance the material understanding.

- Advanced modelling of MEA (12 hours): Knowledge modelling is used to understand mechanism in membrane electrode assembly (MEA) to improve efficiency, detect faulty operation. This part deals with mass and charge transfer in GDE and membrane, Electrochemical kinetics, and EIS (12h)
- Transport phenomena (4 hours): in this lecture a detailed discussion on transport processes (already briefly described in the FC modelling module) is presented. The main gas diffusion models are discussed, as well as the application areas: Fick, Stefan-Maxwell and Dusty-gas models are described and explained. Diffusion in porous and non-porous domains is discussed. In the same way, according to the analogy between different transport phenomena, momentum (Navier-Stokes equations) and energy (Fourier's Law) balances are described.
- Electrochemical modelling (2 hours): the lecture is an insight on contents briefly discussed in the mandatory course. The phenomena leading to irreversibilities producing overvoltages (and thus a polarisation loss) are deeply described. Butler-Volmer equation for electrochemical reactions modelling is presented. The role of ionic conductivity in charge transport is briefly discussed.
- SOFCs heterogeneous chemistry modelling (1 hour): the modelling of kinetics related to heterogeneous reactions occurring within a solid catalyst is presented. Modeling the reactions means to find a suitable mathematical description of the physics that allows to calculate the rates of the reactions. The problem of describing the heterogeneous reaction rates has been addressed in the SOFC literature in two different ways: (i) by using global expressions for the calculation of an overall reaction rate or (ii) through detailed kinetic models that include intermediate reaction steps. Both the approaches are based on the mean field approximation, which describes the surface state with average quantities and neglects the non-uniformity of the catalytic surfaces.
- SOFCs modelling: multidimensional approach (1 hour): This lecture completes the overview on multidimensional modelling started within the mandatory module. 2-D models for cells and stack repeating units (SRU) are described both for planar and tubular cell configuration. 3-D models are generally used for the simulation at full-stack or SRU level to accurately describe fluidic and thermal fields. An example of 3-D model is described. The model describes an anode supported planar SOFC with corrugated bipolar plates acting both as gas channels and current collectors
- Insights on kinetics and charge transfer (1.5 hours): the methodologies used to model the elementary reactions/steps occurring at different scales (within the active sites or inside a discrete cell of the domain) are here presented. The overview presents the Density Functional Theory-based methods, Molecular Dynamics and Monte Carlo techniques, Discrete elements (and phase field) methods, Lattice Boltzmann methods and finally continuum approach modelling.

- Image analysis and EIS for SOFCs (2 hours): In this section the attention is focused on SOFCs devices at electrode/cell level. In particular, two characterisation techniques to evaluate and enhance some key properties of the electrode/cell that can improve the SOFC cell/system performance: a) Image analysis and b) Electrochemical Impedance Spectroscopy (EIS). Images analysis techniques and structures reconstruction methods have been proposed as powerful and reliable tools in the fuel cell research to characterise the cells in terms of microscopic features, mechanical and thermal properties. EIS is a powerful tool for electrochemical characterization of the cells, helping the knowledge about polarisation losses. It is based on the consideration that electrical impedance of a system is defined as its complex and frequency dependent resistance, i.e., the correlation between voltage and current.
- Seminar: modelling of a power-to-power system based on fuel cells (2 hours): this seminar describes the research activity on energy storage in remote areas, as renewable energy sources (RES) can represent a cost-efficient and decarbonised alternative to the on-site expensive and polluting electricity generation through traditional fossil fuels. Due to RES fluctuation and intermittency, energy storage can be a game changer to improve self-sufficiency in isolated micro-grid and off-grid remote areas. The energy storage can be developed effectively with the application of hydrogen and fuel cell technologies, usually in hybrid configuration with closed batteries: Power-to-Power (P2P) systems. A case study on a Mediterranean island and on the power management strategies is presented.

3.11.2 Learning outcomes

By the end of the module students will have built

- Know-how on modelling of the fundamental physical phenomena occurring inside the active layers (electrodes, GDE) and separator (electrolyte membrane);
- A solid background in order to design and optimise assembly of fuel cells and electrolysers and diagnose defects.

4 Additional modules

4.1 A1 - Electrocatalysis (Grenoble-INP)

4.1.1 Module content

This additional module (20 h) focuses on the complex aspects for real electrochemical systems: role of the double layer, complex redox mechanisms. The lectures provide an overview of interfacial electrochemistry and outline the mechanisms of electrocatalysis.

The module is divided into 4 parts:

<u>Overview of electrochemical interface and models of the double layer.</u>

- Basics: Electrochemical interface and Electrochemical potential
- Structural models of the electrochemical double layer: Anisotropy of (volume) charge at the interface, Helmholtz, Gouy-Chapmann & Stern models, Specific adsorption at blocking electrode (Grahame mode)

<u>Thermodynamics</u>

- Thermodynamics of the interface: Gibbs adsorption isotherm, Electrocapillary equation
- Specific adsorption at blocking electrode: Neutral species and ions, Electro-sorption isotherm, Co-adsorption

<u>Charge transfer</u>

- Basics of electrochemical kinetics
- Effect of the double layer structure on kinetics
- Charge transfer with specifically adsorbed specie

<u>Electrocatalysis</u>

- Material structural / composition effects vs. electrocatalytic activity
- Adsorbed intermediates in electrocatalysis Volumic (gas diffusion) electrodes
- Selectivity
- Durability – poisoning effect

4.1.2 Learning outcomes

By the end of the module students will be able to

- Describe interfacial chemistry and processes on electrode and electrocatalysis phenomena;
- Describe thermodynamics, kinetics laws involved at the interface;
- Characterise electrocatalysis activity and important controlling factors for catalysis design.

4.2 A2 – Power to Gas Technologies (UBHAM)

4.2.1 Module content

Because of the environmental challenges of energy generation such as pollution and nuclear waste disposal, the use of renewable energies has become increasingly important. The commonly used renewable sources for electricity generation include: solar, hydro, wind, tidal, amongst others. However, the generation of electricity from these renewable sources has a major drawback: variability. For instance, the amount of electricity generated from sunshine and wind is strongly dependent upon solar radiation intensity and wind speed, respectively. Hence, storing any excess of production electricity at high production rates for times of low production and high demand is essential.

The most commonly used technology for electricity storage is batteries, but the lifetime and costs of the batteries are the major issues for long-term electricity storage. Other than with the direct storage of electricity, the approach of Power-to-Gas (PtG or P2G) is to convert the excess electricity into a chemical form of energy and then store this. Solids, liquids and gases are far easier to store with far lower or even zero losses. P2G is the technology to master the latter, one example being the use of excess electricity for water electrolysis to produce hydrogen and oxygen. The hydrogen produced can be directly used for fuel cells or further converted into methane for storage.

This module was created in the context of a Global Challenge Research Fund (GCRF, UK) project with Indonesia. It formed the base of an (unsuccessful) project application for a reversible Solid Oxide Cell R&D project aimed at supporting energy security for the 6,000 island communities of the Indonesian archipelago.

The module leans more towards a CPD and MOOC approach in that it is divided into smaller units and does not follow strict 'lecture/lesson' principles as usual at a university and in university teaching. It is therefore included here as an 'additional' module since it is suitable to deliver deeper insight into this application of topics raised earlier in the course (e.g. in C2 and C3, as well as O10 etc.), especially since this module establishes the greater context with energy policies, energy security and the actual fuel cell/electrolyser technology.

The module is divided into the following five online elements:

<u>Part 1</u>

Unit 1 An Introduction to Energy Storage

Unit 2 An Introduction to Power-to-Gas

Unit 3 Hydrogen as an Energy Vector

<u>Part 2</u>

Fundamentals of Fuel Cells 1 & 2

<u>Part 3</u>

Unit 1 Low-Temperature Electrolysis

Unit 2 High-Temperature Electrolysis and Co-Electrolysis

Part 4

Unit 1: Synthetic Fuel Production by PtG

Unit 2 Sources of Electricity, CO_2, and H_2O

Unit 3 An Introduction to Hydrogen Infrastructure

Unit 4 Hydrogen Storage

Unit 5 Hydrogen Distribution

Unit 6 Methane Storage

Part 5

Unit 1 Hydrogen in Transport Applications

Unit 2 Hydrogen in Stationary Applications

Unit 3 Industrial uses of hydrogen

And further includes three case studies:

Case Study 1 - Energy Storage: California, US

Case Study 2 - Power-to-Gas Market: Indonesia

Case Study 3 - Feasibility of Power-to-Gas Technology in Japan

4.2.2 Learning outcomes

By the end of the module students will be able to:

- Explain the principles of P2G technologies and the underlying technological principles;
- Understand and discuss the energy infrastructure context and the connection to renewable energy integration;
- Design the outline of a P2G system embedded in a national energy system.