



Fuel Cell & Hydrogen Technologies JP

SP2: Catalyst and Electrodes

Borovetz, Bulgaria

June 2nd and 3rd 2014

Joint Programme on Fuel cells and Hydrogen technologies (FCs & H₂)

EERA FCH2-SP2 WORKSHOP in frame of EIA10

Bridging experimental and numerical research:

development and optimization of advanced characterization tools – Electrochemical Impedance Spectroscopy



Luis Colmenares

SINTEF Materials and Chemistry

European Energy Research Alliance

Letter of Intent for EERA

Paris 2008 – LOI EERA



- Based on own resources
- EERA aims to be light & non-bureaucratic

- Alliance that aims to accelerate development of new energy technologies
 - Harmonisation of national and EC programmes, decrease fragmentation
- Called for in the Strategic Energy Technology (SET) Plan
- Participation in EERA in principle open to all research organisations
 - Not just a membership; need to bring in significant R&D capacity

The original idea

Joint Programming –

What kind of cooperation can be foreseen?

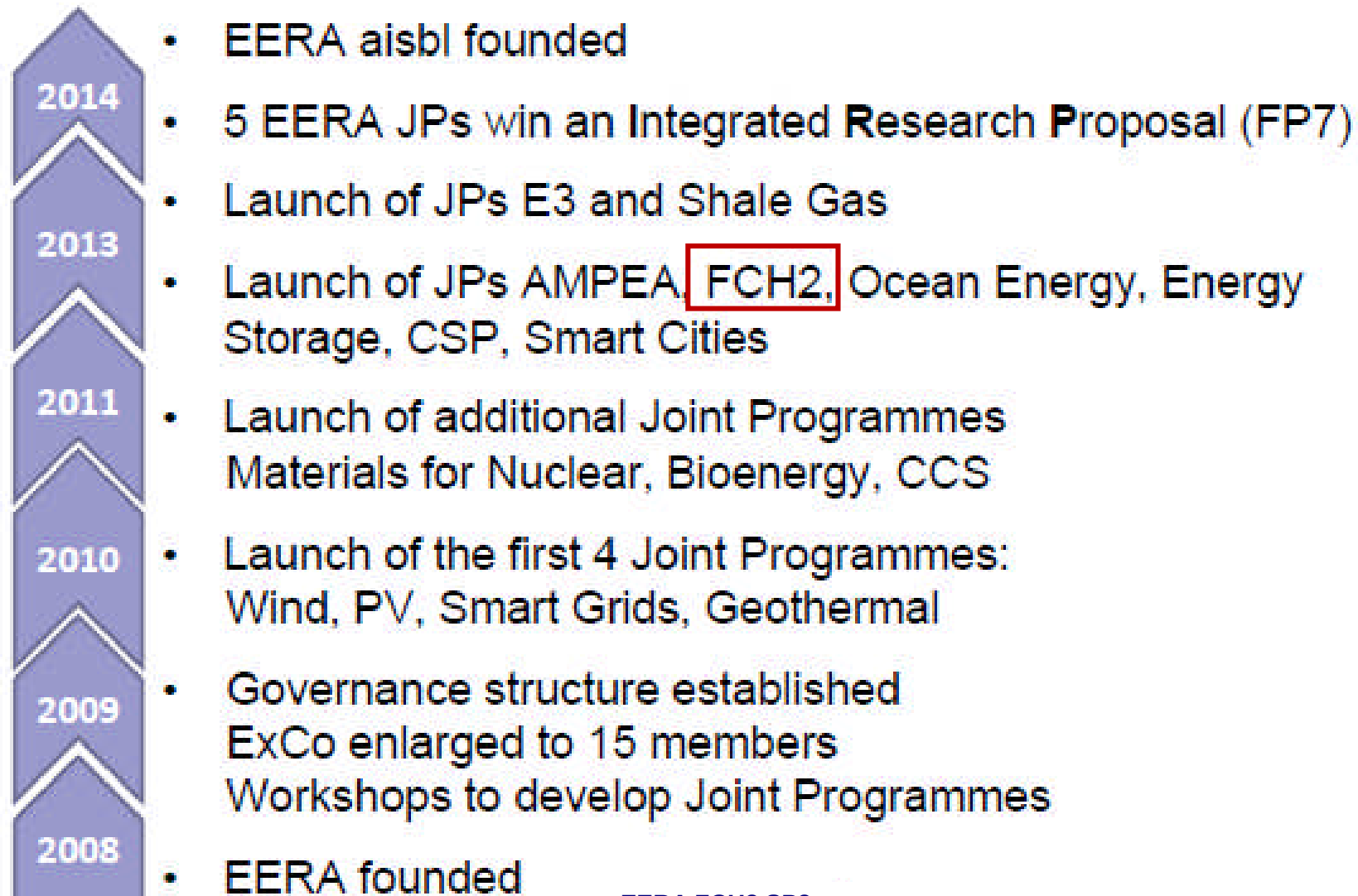
- Harmonisation of research programmes
 - Exchange of information
 - Exchange of personnel
 - Common strategy to tackle (new) research questions
 - Too many topics for a single institute
 - Avoid duplication, ensure complementary of programmes
 - Agree on who does what (and share results)
- Facilities
 - Sharing of facilities
 - Building new facilities
 - Owned by multiple institutes

} Insufficient for EERA

} A breakthrough

European Energy Research Alliance

Progress in the last 6 years



FCs & H₂ Joint Programme

Background

- FCs&H₂ for transport, stationary and portable applications → wide base for high (CHP) efficiency, modularity, low environmental impact
- FCs&H₂ in the SET-plan as part of key technologies to reach 20-20-20 goals and 60-80% GHG reduction by 2050
- Significant technological progress in the last decade
- FCs&H₂ are well developed and almost mature technologies but:
long-term deployment into the market still needs long-term (basic and breakthrough) research in order to beat cost and lifetime issues.
- Foreseen commercialisation of passenger vehicles and of fuel cells in the field of stationary applications from 2020

JP FCH2: Assessment of the operation

Work-programme of the European Industrial Initiative (EII), the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) *does not have basic or long-term research as focal point.*

FCH JU → the prioritisation of activities related to fuel cells and hydrogen technologies has been given to industrial stakeholders.

→ *Most of the research is mainly product/demonstration oriented*

Long term research is still needed – setting of the

Joint Program on Fuel Cells and Hydrogen Technologies (JP FCH2) for

1. assembling critical mass of research capability, and
2. provide the strategic leadership in defining the research agenda for the next phase of fundamental and break-through research in this field.

JP FCH2: Assessment of the operation

- The EERA Joint Program on Fuel Cells and Hydrogen Technologies was **officially launched** at the SET-Plan Conference in **November 2011** in Warsaw.
- **Description of Work** (DoW) has been finalized in late **October 2011**.
- Setting of the **Implementation Plan** for the JP FCH2 basic R&D until 2020 is **under definition** among all the participants.
- EERA is **open to all applicants** – but contributions from participants should strengthen the JP objectives.
- The EERA JP FCH2 had currently **24** partners which contributed efforts of **160** person-years/year.

JP FCH2: Objectives

The overall objectives of this Joint Program are:

- to align medium to long-term pre-competitive research activities at EERA institutes and associated institutions to create a technical-scientific basis for further improvement of Fuel Cells and Hydrogen technologies.
- to highlight the main areas where long-term research activities will help these technologies to reach breakthroughs towards real market applications
- to explore the possibilities for joint European technology development, and
- to identify and exploit the potential synergies therein in order to enhance the solution of the problems that still prevent commercialization of fuel cells and hydrogen technologies

JP FCH2 will initially focus on fuel cell and water electrolyser issues and related electrochemical aspects, in addition to a sub-programme on non-electrochemical hydrogen production and handling cells and hydrogen technologies.

Partnership and Resources

	Name	Country	Role	Person y/y
1	ENEA	Italy	Participant JP coord.	13
2	SINTEF	Norway	Participant SP Coord.	5
3	UoB	UK	Participant SP Coord.	18
4	Risø-DTU	Denmark	Participant	8
5	FZ-Jülich	Germany	Participant SP Coord.	5
6	DLR	Germany	Participant	6,5
7	CNRS	France	Participant SP Coord.	18
8	JRC	Netherlands	Participant	5
9	CEA	France	Participant SP Coord.	6,1
10	VTT	Finland	Participant SP Coord.	5,5
11	CNR	Italy	Participant	12,6
12	POLITO	Italy	Associate to ENEA	1,2
13	TUD	Netherlands	Participant	8
14	UoU	UK	Associate to UoB	2
15	CIEMAT	Spain	Participant	5
16	IMPPAN	Poland	Associate to UoB	1
17	CRS4	Italy	Participant	5
18	CUTEC	Germany	Participant	6
19	IK4	Spain	Participant	5
20	TECNALIA	Spain	Participant	5
21	Un. of Lorraine	France	Participant	5
22	UKERC	UK	Participant	13
23	Un. of Genoa	Italy	Associate to ENEA	1,5
24	Un. of Bologna	Italy	Participant	6
25	Bulgarian A. S.	Bulgaria	Participant	12
	SUM			176,4

25 members

- 21 participants
- 4 associates
- 11 countries

6 Sub Programs

HR commitment

176,4 py/y

JP FCH2: Organization

The JP is coordinated since 2011 by Angelo Moreno, ENEA (IT)

JP FCH2 is structured into the following 6 sub-programs:

SP 1: **Electrolytes**, *Deborah Jones*, CNRS (FR)

SP 2: **Catalysts & Electrodes**, *Luis Colmenares*, SINTEF (NO)

SP 3: **Stack materials and Design**: *Josef Mertens*, FZ Juelich (DE)

SP 4: **Systems**: *Jari Kiviaho*, VTT (FI)

SP 5: **Modelling/Validation/Diagnosis**: *Mathias Gerard*, CEA (FR)

SP 6: **H2 Production and Handling**: *Robert Steinberger-Wilkens* (UKERC)

Joint Program Management Board (JPMB). The JPMB consists of all subprogram leaders and the Joint Program Coordinator.

Joint Program Steering Committee (JPSC). The JPSC consists of all participants which contribute at least 5 person-years/year to the program.

Main Activities: SP1 Electrolytes

- ***Main goal***

Bridge the temperature gap. Develop stable, high performance and low cost electrolytes for polymer-based, solid oxide and proton conducting ceramic systems required for mid to long term development of fuel cell and electrolyser technologies.

- ***R&D objectives***

- New high temperature membranes
- Improved processing methods (i.e. Nanoscale structuring)
- New conducting electrolytes: anion conducting, solid oxide, proton conducting
- Understanding of degradation mechanisms
- Set up of accelerated testing methods

Main Activities: SP2 Catalyst & Electrodes

- ***Main Goal***

Highly active, low cost and durable catalyst/electrode based on the reduction of loading and the replacement of Pt group metals. Definition of appropriate routes for generating tailor-made catalysts

- ***R&D objectives***

- Synthesis of new catalysts tailored on real operating conditions
- Optimisation of catalyst layer, deposition techniques, membrane assembling
- Low Pt load membranes both for FC and electrolyzers
- Ceramic FC and electrolyzers, possibly low temperature

Main Activities: SP3 Stack materials and Design

- ***Main Goal***

Cost effective manufacturing of 'robust' stacks: high tolerance to thermal and load cycling and to a defined degree of 'mistreatment' in the form of vibration, transient operation, fuel and air impurities etc.

- ***R&D objectives***

- materials and novel design development (Interconnect, bipolar plates, contacting and gas diffusion layers)
- materials processing
- component design
- New sealing materials for HTFC, LTFC and electrolyzers
- Novel stack and integrated modules design

Main Activities: SP4 Systems

- ***Main goal***

Development of innovative fuel cell system concepts, optimizing integration, compactness, robustness, foot print with new components with low costs, prolonged life-time and availability of components.

- ***R&D objectives***

- Materials:

- New materials/coatings corrosion resistant
 - New catalysts both for fuel processing and fuel upgrade/clean up

- Components for heat management, failure detection, air supply, water management, power conditioning,

- Sensors, diagnostic tools, system controls

- New system concept: process flow and thermodynamic optimisations

Main Activities: SP5 Modelling, Validation and Diagnosis

- **Main Goal**

Three level of investigations: cell, stack, system: Better understanding of the degradation mechanisms and the relationships with operating conditions. Development of mathematical description of phenomena, specifications of experimental development of accelerated aging tests

- **R&D objectives**

- Cell, investigated phenomena: flow channels, GDL, catalyst layer, membranes; model validation.

- Stack: thermal and water management, non isothermal operations.

- Systems: analysis of performances and degradations, model development, control strategies under realistic operating conditions

Main Activities: SP6 Hydrogen Production and Handling

- ***Main goal***

Cost effective and efficient non-electrochemical H₂ production methods by improving materials and identifying superior novel materials, optimizing materials processing, and developing new, break-through designs for H₂ production systems.

- ***R&D objectives***

- Optimisation of different possible production methods: Thermo chemical; Biochemical; Algae; Photo catalysis; Thermolysis;
- Improve the storage of compressed and liquid hydrogen lowering energy demand and losses (new insulation materials)
- Critical review on C&S requirements
- Pre normative research to contribute to the development of new C&S for safe hydrogen production technologies. Focus on H₂ purity

- ***JP Coordinator:***
Angelo Moreno (angelo.moreno@enea.it)
Stephen McPhail
(Stephen.mcPhail@enea.it)
- ***The EERA Secretariat:***
Ingo Bunzeck (bunzeck@ecn.nl)



Fuel Cell & Hydrogen Technologies JP

SP2: Catalyst and Electrodes

Borovetz, Bulgaria

June 2nd and 3rd 2014

EERA JP FCs&H2 SP2: Catalyst and Electrodes



SP2 Coordinators

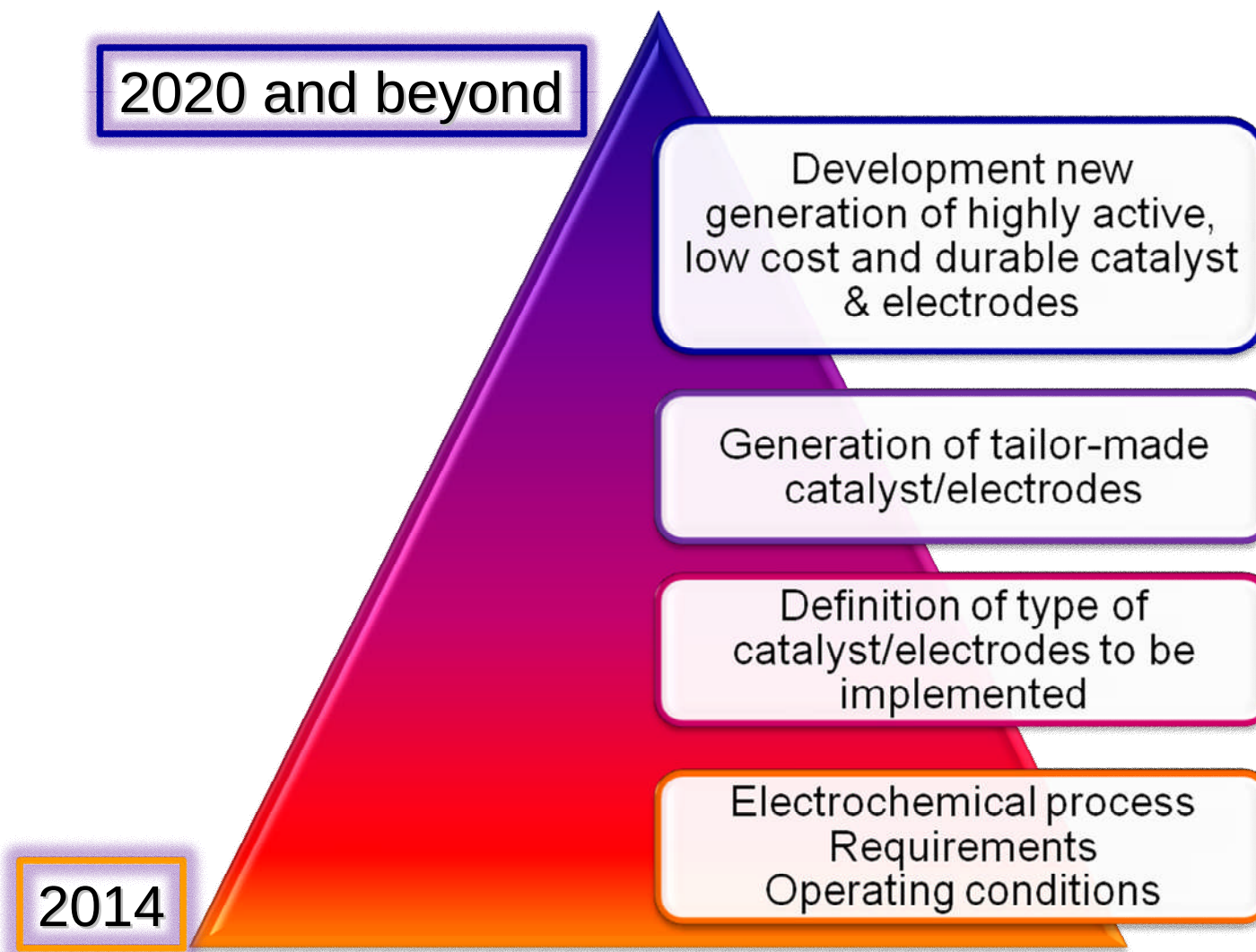
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SP2: Catalyst & Electrodes



SP2: Organisation of work (DoW)

SP 2.1 Catalysts Synthesis

SP 2.2 Polymer Membrane Based Fuel Cells

SP 2.3 Polymer Membrane Based Electrolysers

SP 2.4 Ceramic Cells (FC/EC)

→ *Four topics which results in almost 20 sub-topics to be implemented ...*

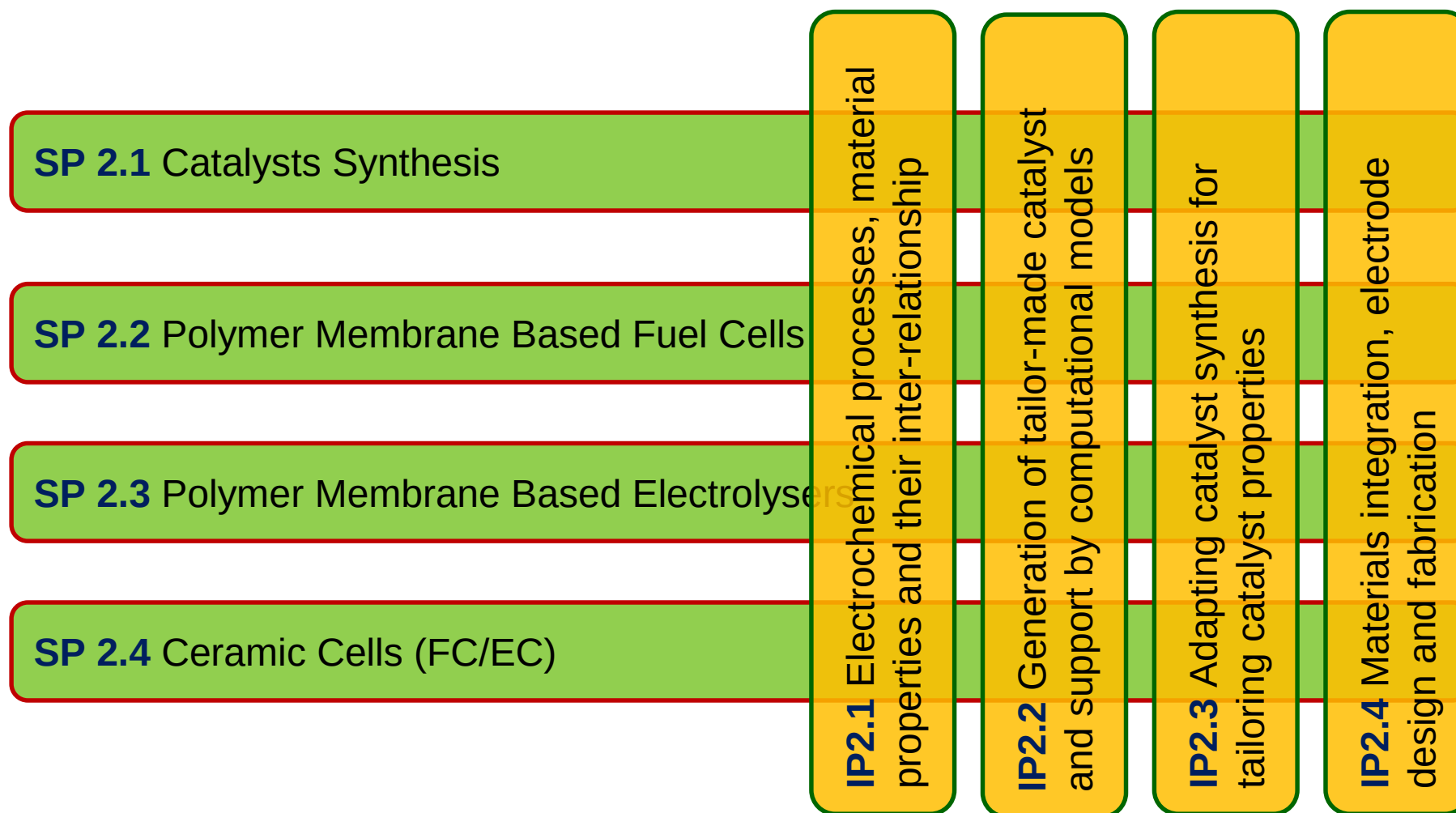
SP2: Organisation – Participants

Organization	Country	Human Resources Committed (py/y)
SINTEF	Norway	3.0
CIEMAT	Spain	4.0
UKERC	UK	13.5
Risø-DTU	Denmark	4.0
CNRS	France	5.0
CEA	France	0.6
ENEA	Italy	3.0
DLR	Germany	1.0
TUD	Netherlands	2.0
CNR	Italy	5.2
Uni. Bologna	Italy	1.0
FZJ	Germany	1.0
IK4	Spain	3.0
JRC	Belgium	1.5
BAS-IEES	Bulgaria	3.7
CSIC	Spain	0.67
Total		52,17

SP2: Objectives – keys topics

- 1) Gain a better fundamental understanding of FC&EC electrochemical processes (including determination of active surface and degradation mechanisms), material properties and the inter-relationship among catalyst structure, reactivity and stability.
- 2) Computational assisted design of tailor-made electrodes, catalyst and supports. Modeling of electrode reactions and material transport.
- 3) Development, adaptation and optimization of material synthesis processes to achieve tailor-made catalyst (electrodes, catalysts and supports) properties.
- 4) Electrode engineering to integrate and optimize electrodes (catalysts and supports) into cell architectures.
- 5) Investigation of new electrochemical processes involving alternative fuels (alcohols, biofuels, low molecular weight hydrocarbons).

SP2: Activities – Work organization DoW / IP



SP2: Implementation Plan

IP 2.1 Fundamental understanding of FC & EC electrochemical processes and materials

Main goals:

- Gain a better comprehension of the relationship between catalyst/electrode chemical nature and its activity under application relevant conditions. This addresses single materials (e.g. catalysts core-shell structures) but also materials combinations (e.g. catalyst support interactions at various temperatures and atmospheres) and especially interfaces (electrode–electrolyte interface). This understanding should lead to:
- Identify performance limiting steps and lifetime limiting processes, and how they correlate with structural parameters, chemical and electronic properties of materials and interfaces.
- Optimize catalyst and electrode properties for the electrochemical reaction considered, i.e. oxygen reduction, fuel oxidation, and water oxidation and reduction.

IP 2.2 Design and generation of tailor-made electrodes, catalyst and supports

Main goals:

- Develop and implement a systematic approach to design new materials for fuel cells and electrolysis cells (e.g. using computational materials design/DFT calculations). This can be used further to tune catalyst and support properties (structure/reactivity/stability) to be adapted to specific electrochemical process and applied operation conditions.
- Assess of new catalyst designs and electrode architectures.
- Develop electrode materials for new/advanced electrochemical cells.

IP 2.3 Adapting catalyst synthesis for tailoring catalyst properties

Main goals:

- Explore and develop new fabrication processes for tailor-made electro catalysts and electrode materials. This will take either already existing routes up to a technically relevant level or include the search for alternative fabrication techniques in cases where no known principle can be applied for.
- Include appropriate quality assurance throughout the process. The fabrication processes should preferably be environmentally friendly, low-cost, fast and with low energy usage.

IP 2.4 Materials integration, electrode design and fabrication

Main goals:

- Realize and characterise advanced electro-catalysts and electrodes by developing and optimizing their processing method. This includes the optimisation of manufacturing parameters for electrode production (e.g. ink composition, three-dimensional electrodes) and their relationship with the Fuel cell and Electrolysis Cell functionality
- Develop new manufacturing techniques. The performance of the cells needs to be evaluated by investigating as much as functional aspects as possible (e.g. electrocatalytic activity, fuel efficiency, transport (water / gas, conductivity) on a technically relevant scale.

SP2: IP Estimation of budget & nr. projects

Topics	Nr. projects	Budget MEuro	Priority
1. Fundamental understanding of FC & EC electrochemical processes and materials	24	72	1.7
2. Design of tailor-made electrodes, catalyst and supports	35	133	1.6
3. Adapting catalyst synthesis for tailoring catalyst properties	16	67	1.9
4. Materials integration, electrode design and fabrication	20	100	1.7
SP2 Implementation Plan	95	372	1.7

SP2: Activities (surveys) and results

Expertise and Interest

T1: Catalyst synthesis

T2: PEM-based FC

T3: PEM-based EC

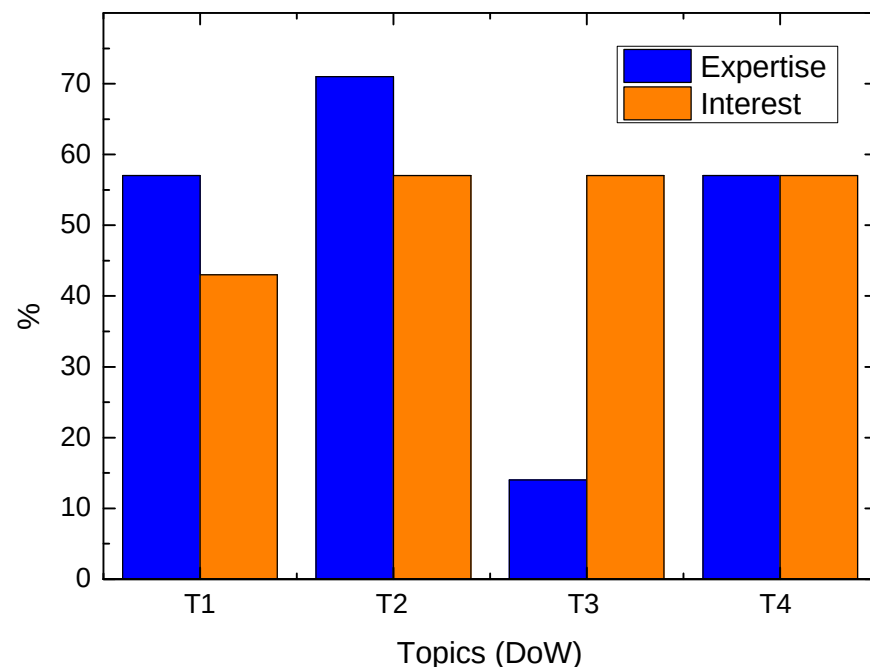
T4: Ceramic cell (FC/EC)

IP2.1: Electroch. processes, material properties and their inter-relationship

IP2.2: Generation of tailor-made catalyst and support by computational models

IP2.3: Adapting catalyst synthesis for tailoring catalyst properties

IP2.4: Materials integration, electrode design and fabrication



T1 → IP2.3 > 2.2 > 2.4 > 2.1

T2 → IP2.1 > 2.2 ≈ 2.3 ≈ 2.4

T3 → IP2.2 > 2.4 > 2.1 > 2.3

T4 → IP2.4 ≈ 2.3 > 2.1 > 2.2

* The numbers reported here is based on information from 7 out of 16 SP2 participants (5 countries)

SP2: Activities – Milestones (IP)

SP2 MS	Milestone Title	Measurable Objectives	Time frame/year
M2.1	Roadmap for FC/EC catalyst/electrodes	- Identifying targets for catalysts/electrodes - SoA catalyst/electrodes - SoA definition of synthesis routes - Report with established synthesis routes, equipment and infrastructure for catalyst/electrode development	2015
M2.2	Alternative electrode materials identified	Electrodes with superior performance compared to SoA	2016
M2.3	Optimisation of catalyst/electrode manufacturing processes	- Optimized preparation methods for electrode - Optimized deposition techniques	2018
M2.4	LT-FC/EC fabrication methods for ultra-low noble metal loadings	Electrodes with same or superior performance compared to SoA	2019

SP2: Activities – Milestones (IP)

SP2 MS	Milestone Title	Measurable Objectives	Time frame/year
M2.5	Computer assisted materials development	Commonly accepted software developed	2020
M2.6	Computer assisted electrode design (architecture) development	Commonly accepted software developed	2020
M2.7	LT-FC/EC Advanced characterization	In-situ and In-operando test center established	>2020
M2.8	IT-FC/EC Advanced characterization	In-situ and In-operando test center established	>2020
M2.9	HT-FC/EC Advanced characterization	In-situ and In-operando test center established	>2020

SP2: Planned activities

- **SP 2.1** Extend the actual actions from the core-group to the whole SP2 participants to increase commitment
- **SP 2.2** Identify the main expertise, interests and 'gaps' of SP2 participants (mapping) to evaluate R&D status / market readiness
- **SP 2.3** SP workshops to define more concrete activities
- **SP 2.4** Compilation of "open issues", challenges, bottlenecks to be overcome
- **SP 2.5** Initiate a process for definition of "projects" within the SP
- ...



Fuel Cells & Hydrogen Technologies JP

SP2: Catalyst and Electrodes

WORKSHOP

**Bridging experimental and numerical research:
development and optimization of advanced characterization tools based
on Electrochemical Impedance Spectroscopy**

In frame of

10th International Symposium on Electrochemical Impedance Analysis 2014 (1 – 5 June)



Workshop: background

Developing a new generation highly active, low cost and durable catalysts and electrodes. identification of the requirements of each electrochemical process

which defines the type of electrode to be used.

harmonizing activities with other SPs, especially with SP5 M/V/D

rational catalyst and electrode design would be achieved by the joint development and optimization of advanced characterization tools combining numerical and experimental research.

- Numerical modelling must be completed by specific experimental tests that provide input for the model and model validation

- **coupling of EIS with microstructural characterization** (post mortem analysis) can strongly increase the information capabilities.

- Only by correct experimental validation, detailed simulation effectively can accelerate and optimize the achievement of next-generation catalyst and electrodes for fuel cell and electrochemical cell systems.

Workshop: Scope

- What impedance can contribute to develop advanced characterization, catalyst and experimental validation tests.
- What is the best of what we are doing now, in which direction should we go for further development
- what will be the foreseen challenges to further develop EIS as one of the most powerful techniques to support the experimental validation approaches

Workshop: Invitation for an open discussion

Topic I: Interpretation of the experimental data:

- Interpretation of the experimental data:
 - *Can construction of impedance models be avoided/replaced with more simple procedures that extract valuable information?*
- Need for harmonizing (standardizing) testing procedures and data analysis for Real-time Diagnosis of FC performance and 'health':
 - *Can EIS help to identify alternative or complementary characterization techniques for real-time monitoring?*
- Advances of combining EIS with other characterization techniques.

Topic II: concerns more instrumentation: Impedance Spectroscopy in Energy Sources Development

- Recent Progress in Impedance Instrumentation
- Advancing Requirements toward Instruments
- D.C. Testing or/and Impedance Spectroscopy?

Thank you for your attention

BUT, especial thanks to:

- Prof. D. Vladikova

tee, but especially to Gergana Raikova and Neli Gospodinova

- P. Holtappels

A. Àrico

S. Barison

P. Brault

- C. Paoletti

S. McPhail

F. Alcaide

- All the workshop speakers

C. Boigues Muñoz

M. Cassir

C. Chatzichristodoulou

A. Barbucci

- and you for joining our workshop*

Thank you for your attention

We are looking forward to listening to
your comments, suggestions, ideas and doubts
and even better to welcome you and your knowledge
and competence to the
EERA JP FCs&H2

SP2 Supporting Slides

SP2: Activities (surveys) and results

e	i	Topic
57	43	T1 Catalyst Synthesis
71	57	T2 Polymer Membrane Based Fuel Cells
14	57	T3 <i>Polymer Membrane Based Electrolysers</i>
57	57	T4 Ceramic cells (Fuel and Electrolysis Cells – FC / EC)

e	i	T1. Catalyst Synthesis
0	57	T1.A Develop a DFT model for selecting 'promising' electrocatalysts (mono-; bi-; multi-metallic, alloy, core-shell) with high activity/stability
14	43	T1.B Bifunctional electrodes for unitized regenerative fuel cells
86	71	T1.C Develop novel inorganic and organic electrocatalysts based on e.g.: Wet Chemistry (WC) / Sono-electrochemistry (SE) / Flame Spray Pyrolysis (FSP) / Physical Vapor Deposition (PVD) / Magnetron Sputtering
57	57	T1.E Advanced ex-situ and in-situ characterization (physically and electrochemically)

* The numbers reported here is based on information from 7 SP2 participants (5 countries)

SP2: Activities (surveys) and results

e	i	T2. Polymer Membrane Based Fuel Cells	
14	57	T2.A	<i>Identify nano-structured PEMFC supports based on carbides, nitrides and oxides</i>
43	43	T2.B	Study catalysts bases on non-noble metal materials (non-PGM) including other than carbon support materials
57	43	T2.C	Optimize the preparation methods for electrode inks and deposition technique
57	43	T2.D	Study catalyst layer optimisation for effective water and ionic transport
57	57	T2.E	<i>Implement ex-situ and in-situ electrochemical catalyst and support characterization</i>
43	43	T2.F	Study the catalytic activity and electrochemical characterization of the interface anode/electrolyte
57	57	T2.G	<i>Study activity/stability of electrodes in half cells and membrane electrode assemblies (MEA) under realistic operation conditions</i>

e	i	T3. Polymer Membrane Based Electrolysers	
14	57	T3.A	<i>Synthesis of supported OER electrocatalysts with low noble metal content</i>
14	57	T3.B	<i>Nano-structured catalyst for alkaline membrane electrolyser</i>

* The numbers reported here is based on information from 7 SP2 participants (5 countries)

SP2: Activities (surveys) and results

e	i	T4.A.1 Fuel electrodes – Intermediate Temperature – FC / EC (200 – 600 °C)	
14	43	T4.A.1a	Fuel electrodes for proton conducting electrolytes
14	57	T4.A.1b	Electro-catalysts (including supports) for electrochemical synthesis of e.g. methanol, ammonia <i>via</i> electrolysis

e	i	T4.A.2 Fuel electrodes – High Temperature – SOFC / SOEC (600 – 950 °C)	
43	57	T4.A.2a	Addressing materials, processing, cell concepts reaction mechanisms
29	57	T4.A.2b	Development of more robust electrodes (high tolerance to impurities)
29	57	T4.A.2c	Direct hydrocarbon, low molecular weight fuels converting electrodes (SOFC/MCFC)
0	14	T4.A.2d	Direct carbon fuel cells (MCFC/SOFC)
0	43	T4.A.2e	Co-electrolysis (CO ₂ & H ₂ O) to syngas and integrated CH ₄ /C production
14	43	T4.A.2f	Pressurized operation

* The numbers reported here is based on information from 7 SP2 participants (5 countries)

SP2: Activities (surveys) and results

e	i	T4.B.1 Air electrodes – Intermediate Temperature – FC / EC (200 – 600 °C)	
43	57	T4.B.1a	<i>Development of oxygen electrodes for IT SOFC</i>
14	43	T4.B.1b	<i>Development of air electrodes for proton conducting electrolytes</i>
14	57	T4.B.1c	<i>Development of air electrodes (materials, microstructure design) for oxygen reduction and evolution at 200 – 400 °C on OH⁻, HCO³⁻-H⁺ conducting electrolytes (Ag, perovskites)</i>

e	i	T4.B.2 Air electrodes – High Temperature – SOFC / SOEC (600 – 950 °C)	
43	43	T4.B.2a	<i>Addressing materials, processing, cell concepts reaction mechanisms</i>
14	14	T4.B.2b	R&D Durability and tolerance to air impurities (H ₂ O, Si, alkali elements)
14	43	T4.B.2c	<i>SOFC cathode activation (e.g. impregnation)</i>

* The numbers reported here is based on information from 7 out 14 SP2 participants (5 countries)

Highlighted points to be included in the discussion

it will be great that each presentation covers points like for example:

- Current problems and challenges
- Role of the EIA for advanced characterization of catalyst/electrode and what kind of information can give for models development and validation
- What we need to improve to develop further the experimental validation using EIS as an advanced characterization technique
- Anything else that you consider relevant to discuss...