Final report

1.1 Project details

Project title	Upscaling Catalyst Fabrication and Application: Incubation of Laboratory Curios to Competitive Fuel Cell Products (UPCAT)
Project identification (program abbrev. and file)	ForskEL-projekt nr. 2015-1-12315
Name of the programme which has funded the project	ForskEl
Project managing company/institution (name and address)	Technical University of Denmark
Project partners	Technical University of Denmark (DTU) University of Southern Denmark (SDU) Danish Technological Institute (DTI) IRD (EWII) Fuel Cells (IRD/EWII) Danish Power Systems (DPS)
CVR (central business register)	
Date for submission	30. November 2018

1.2 Short description of project objective and results

In English

Further improvement in performance, cost and durability of polymer fuel cells is accomplished by synthesis, upscale fabrication and technological utilization of innovative catalysts. Upscale fabrication of carbon supported platinum (Pt/C) and alloy (Pt_xNi and Pt_xCo) nanocatalysts are consummated. Breakthroughs are achieved in synthesis of platinum rare-earth metal alloy nanoparticles. Alternative supports are developed and platinized. Utilization of these materials is explored in electrode manufacturing and fuel cell tests, with performance reaching the national roadmap target 2018. The results are well disseminated, and further exploitation is planned.

På Dansk

Yderligere forbedringer i ydeevne, omkostninger og holdbarhed af polymer brændselsceller er opnået ved syntese, upskaleret fabrikation og teknologisk udnyttelse af innovative katalysatorer. Opskaleret fabrikation af karbon supporterede platin- (Pt/C) og legerings- (Pt_xNi og Pt_xCo) nanokatalysatorer er opnået. I syntesen af metal legeringsnanopartikler mellem platin og sjældne jordarter er der opnået væsentlige gennembrud. Alternative support materialer er blevet udviklet og platineret. Udnyttelsen af disse materialer er blevet prøvet i elektrode fremstilling og brændselscelleundersøgelser, med en ydelse der når det nationale roadmap mål for 2018. Resultaterne er publiceret et stort omfang og yderligere udnyttelse er planlagt.

1.3 Executive summary

The project was divided into 6 work packages and 26 tasks. 20 milestones and 18 deliverables were defined with due time and responsible partners. Through the period of the project, 7 project (half-year) meetings were held jointly with the steering committee meetings. At the meetings working plans were updated and milestones and deliverables were reviewed. In

addition, thematic internal meetings were organized focusing on catalyst synthesis and electrode fabrication. Momentous value was added by the close collaboration of partners with extensive exchange of materials and knowhow.

The project has primarily followed the original research plan with a couple of small deviations. One of the deviations is the exclusion of the thin-film electrode due to unavailable of substrates and need of more effort to synthesis of alloy catalysts.

Specifically 18 out of 20 milestones and 16 out of 18 deliverables are accomplished. In all, 11 deliverable reports are internally available and uploaded on the project homepage. All together 54 items are published as outcomes of the project dissemination.

1.4 Project objectives

The main technical objectives include:

- Development of techniques for fabrication of nanocatalysts targeting at an up-scaled fabrication
- Development of non-carbon based supports and supported catalysts'
- Synthesis of new platinum alloy catalysts, particularly the platinum-lanthanide based alloy catalysts
- Exploration of non-Pt catalysts and application in fuel cells
- Technological innovation of electrodes using the developed new catalysts
- Promotion of fuel cell performance to fulfil national roadmap target 2018

Briefly speaking, UPCAT has addressed all these issues and key technical objectives, i.e. synthesis of supports and catalysts, targeted activity and stability as well as fuel cell performance and durability are fully accomplished.

1.5 Project results and dissemination of results

Major results of the project are summarized below.

1.5.1. Synthesis of Pt_xNi and Pt_xCo nanoparticles

This was carried out by the supercritical flow reactor method developed at DTI. A setup of the reactor is, as shown in Figure 1, consisting of four pumps, four heaters, six vessels and three coolers. The solvent is typically either water (DI) or ethanol and is preheated to temperatures around 250 – 450 °C.

During the project 50 – 70 wt.% Pt/C catalysts were first prepared using high surface area carbon (Ketjenblack, Ensaco, Vulcan, Graphitized, SiC). More efforts were made to prepare 50 – 70 wt.% Pt-M/C alloy catalysts (M = Ni, Co) with nominal alloy composition PtxM (atomic).

Figure 1. Photo of the supercritical flow reactor setup developed at DTI.

The measured ORR mass activities of selected catalysts and commercial catalysts are shown on Figure 2. The highest activity is achieved for Pt_xCo/C, however, both Pt_xCo/C and Pt_xNi/C are more active than the commercial Pt/C and Pt_3Co/C. The best Pt_xCo/C catalyst had an ORR mass activity of 1.5 A/mgPt, which is about five times more active than the tested commercial Pt/C and 3 times higher than the DOE 2020 target.

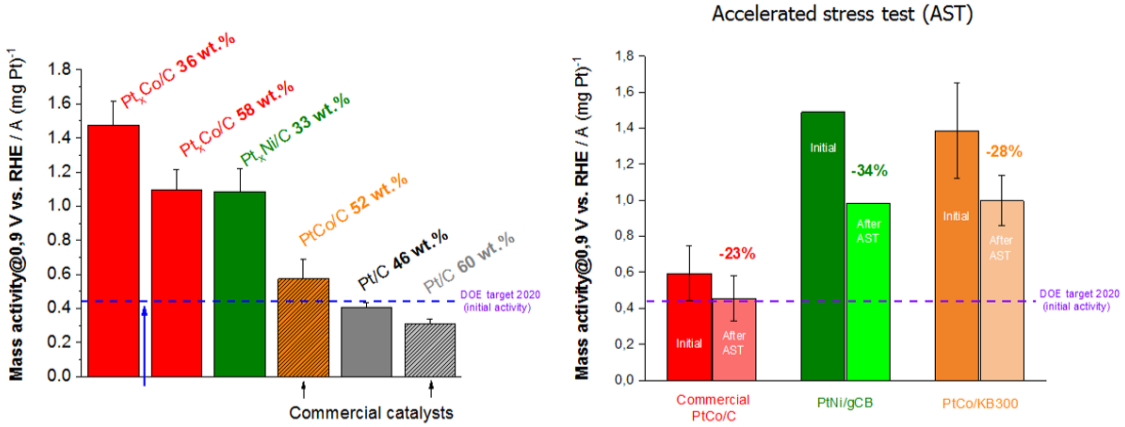

Figure 2. ORR mass activity measurements of PtxM and Pt on carbon compared to commercial catalysts and DOE target 2020, before (Left) and after (Right) accelerated stress test (AST).

1.5.2. Synthesis of platinum-rare earth metal alloy catalysts

The major obstacle for the synthesis of Pt-rare earth metal (Pt-RE) alloy catalysts is the substantial difference between the standard reduction potential of Pt and that for rare earth metals, e.g. 1.188 V for Pt^{2+} and -2.279 V for Gd^{3+}. Furthermore, the rare earth metals tend to form very stable oxides once in contact with water or oxygen. Hence, it is a general consensus that the chemical synthesis of this type of catalysts is only possible in oxygen- and water-free environment. And, a super strong reducing agent such as sodium/liquid ammonia solution is needed for reducing the rare earth metal ion such as Gd^{2+} and Y^{3+}. The first approach was attempted by using organic solvents and ultrapure 100% hydrogen at 800 °C as the reducing agent. The formation of Pt_xY nanoparticles was verified by the XRD patterns (Figure 3, left) and limited enhancement of the activity was also observed (Figure 3, right).

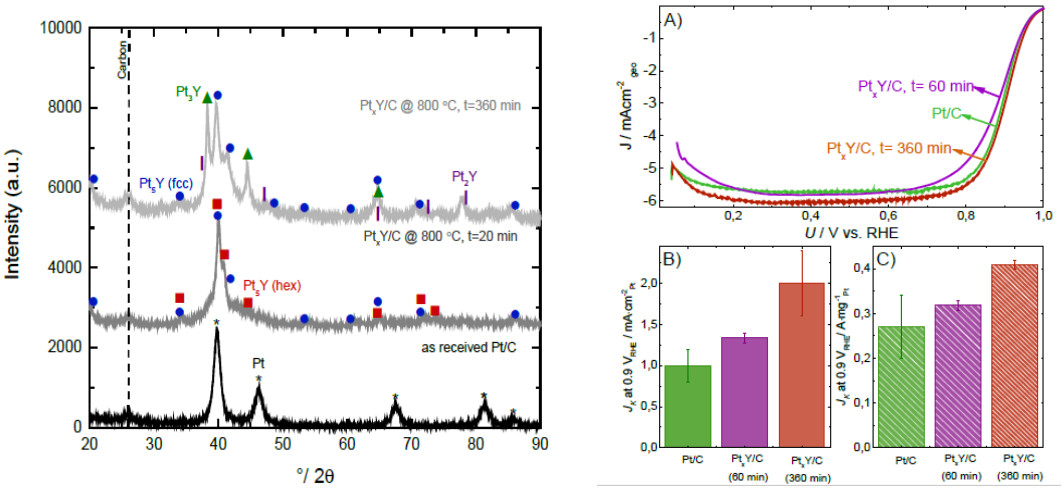

Figure 3. XRD patterns (left) and electrochemical activities (right) of the prepared Pt_xY/C alloy catalysts, as compared with Pt/C reference.

Synthesis of Pt_xY by alkali metal vapor reduction was also successful with no need for glove box, anhydrous precursors or organic media. Alloy particles of 5-10 nm are achieved in batches of ca. 20 mg.

The most successful method was from the inspiration of the synthesis of "single atom catalysts". The synthesis was conducted by heat-treating a mixture of a Pt precursor (e.g., H_2PtCl_6), a rare-earth metal precursor (e.g. $GdCl_3$), a nitrogen-rich precursor (e.g., CN_2H_2), and a carbon support (e.g. black pearls 2000) at 600-900 °C in flowing H_2/Ar.

The crystal structures of the alloy phases were verified by X-ray diffraction (XRD) analysis. As shown in Figure 4, the obtained Pt_xGd/C catalysts consist of two alloy phases, i.e. Pt_3Gd and Pt_2Gd. With increasing the synthesis temperature, the amount of Pt_3Gd phase in the catalyst becomes lower. This result implies the feasibility of tuning the alloy structure simply by varying the synthesis conditions. For typical syntheses, the catalyst depicts alloy nanoparticles with the size of around 6.5 nm.

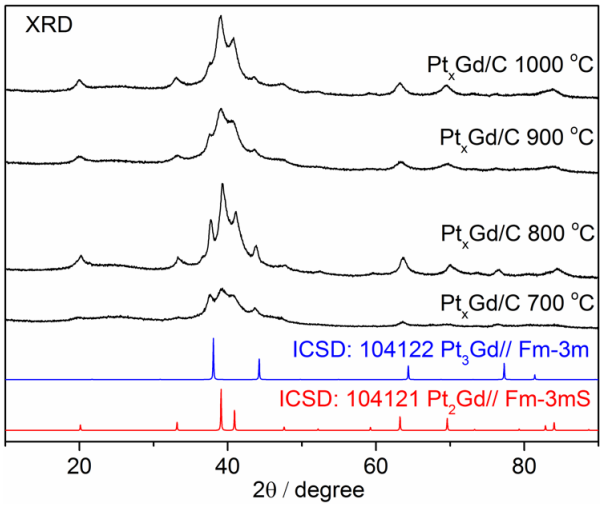

Figure 4 X-ray diffraction (XRD) analysis of Pt_xGd/C catalysts synthesized at different temperatures. The standard XRD patterns of Pt_3Gd (blue line) and Pt_2Gd (red line) are also included for comparison.

The ORR curves of the Pt_xGd/C catalyst and reference Pt/C in 0.1 M $HClO_4$ with the same Pt loading are shown in Fig. 5. Given the smaller ECSA of the Pt_xGd/C catalyst, the positively shifted ORR curve (16 mV in the half-wave potential) is very encouraging. From the ORR Tafel plots, the specific activity of the Pt_xGd/C catalyst is determined to be 2.9 mA cm_{Pt}^{-1} at 0.9 V, which is 4.3 times higher than that of the Pt/C reference catalyst (0.67 mA cm_{Pt}^{-1}). The mass activity is 1.9 times higher than that for the Pt/C catalyst (i.e., 815.3 mA mg_{pt}^{-1} vs. 434.6 mA mg_{pt}^{-1}). Eventually the alloy nanoparticles were prepared in a scale of up to 5 grams.

Two EU patent applications were filed by DTU-Energy.

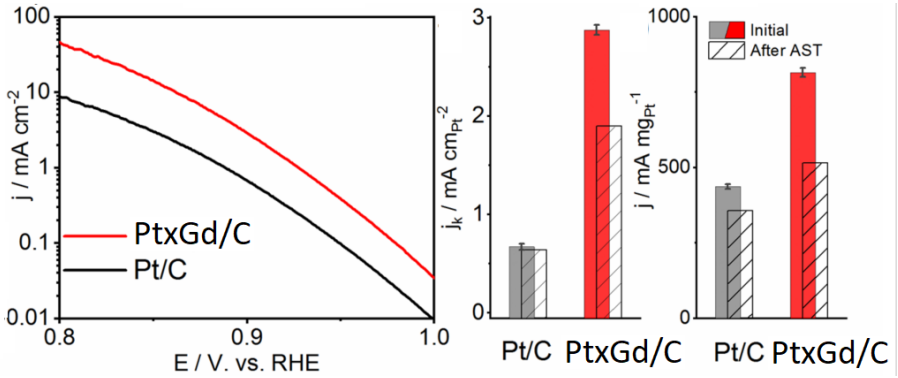

Figure 5. (left) ORR Tafel-plots (specific activity as a function of the electrode potential) of the Pt_xGd/C catalyst and Pt/C in 0.1 M $HClO_4$. (right) Specific activities and mass activities of the Pt_xGd/C catalyst and Pt/C towards the ORR at 0.9 V before and after the AST. The catalyst loadings are the same for both catalysts, i.e. 15μg_{Pt} cm^{-2} on the RDE. The error bars show the standard deviation of the data point from at least three independent measurements.

1.5.3. HT- PEM fuel cell test

At DPS, both cathode and anode catalyst loadings were reduced from 1.5 mg/cm^2 using Pt/C from JM to 0.8 mg/cm^2 using Pt_xCo/C alloy catalysts, corresponding to a reduction of 46%. At the same time the performance was increased by 20 mV at 0.2 A/cm^2, corresponding to a 3% increase. The long-term durability of up to 6000 hours was achieved with an average degradation rate of < 8 µV/h by using a Pt_xCo/C alloy catalyst, as shown in Figure 6.

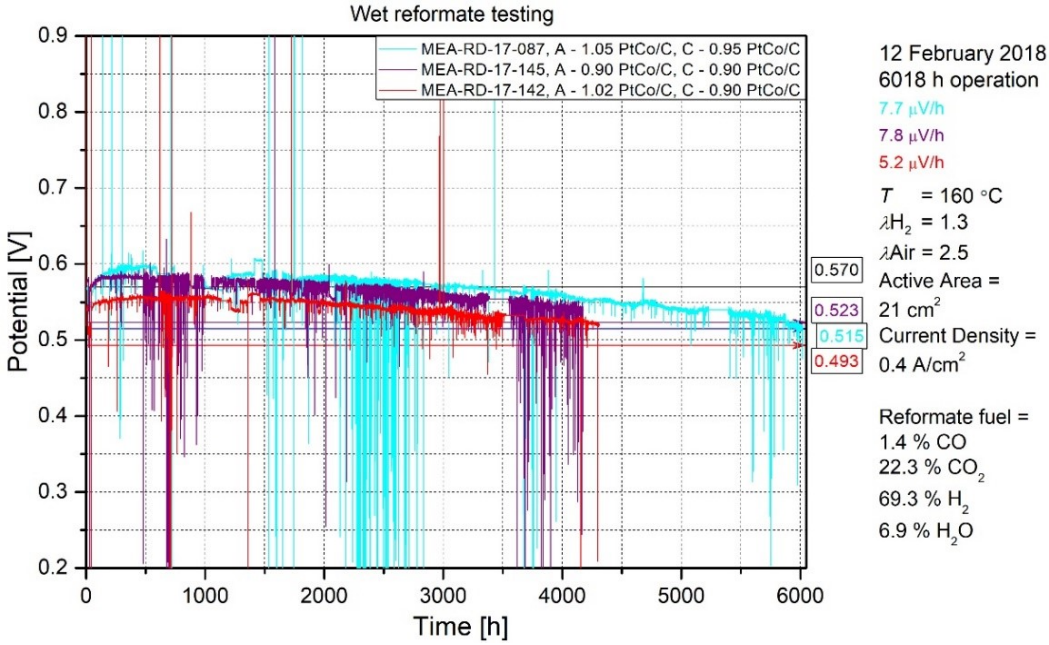

Figure 6. 6000 h lifetime test with PtCo/C catalysts feeding wet reformate fuels as specified in the figure. The cells were operated at a constant current density of 0.4 Acm^{-2} for several thousand hours, with one MEA reaching the target 6000 h at an average degradation rate of 7.7 µV/h. A common degradation rate of 10.9 μVh^{-1} was observed from peak until at least 3000 h for the 3 long-term tested MEAs.

1.5.4. LT-PEM fuel cell test

For the evaluation of the Pt_xCo/C fabricated by DTI, EWII has prepared four different 5 cm^2 MEAs and four analogous 25 cm^2 MEAs for comparison (See Table 1).

Table 1. Details of the MEAs with PtxCo/C cathode and reference MEAs with Pt/C cathode

MEA	Size; number	Cathode	Membrane	Anode
RefPtA	5 cm^2; 2	0.5 mg_{Pt}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
RefPtB	25 cm^2; 2	0.5 mg_{Pt}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
RefCoA	5 cm^2; 2	0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
RefCoB	25 cm^2; 2	0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
DTI25A	5 cm^2; 2	DTI 0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
DTI25B	25 cm^2; 2	DTI 0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
DTI30A	5 cm^2; 2	DTI 0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2
DTI30B	25 cm^2; 2	DTI 0.5 mg_{PtCo}/cm^2	Nafion XL-100	0.3 mg_{PtxRu}/cm^2

First the CCMs were completed by applying anode layer consisting of Pt_xRu/C catalyst with a loading of 0.3 mgPt_xRu/cm2 on the fresh side of the cathode-coated Nafion® XL-100. These CCMs were hot-pressed with GDL to produce the final MEAs for the testing. The IV and power curves are shown in Figure 7. It is seen that the MEA with DTI Pt_x-Co/C cathode (DTI25B) exhibited a performance of 0.70 V at 1.14 A/cm^2. This corresponds to a power density of 800 W/cm^2, which is well above the UPCAT target of 550 mW/cm^2 (i.e. the national LT-PEM Roadmap 2018 target for single-cell MEA performance).

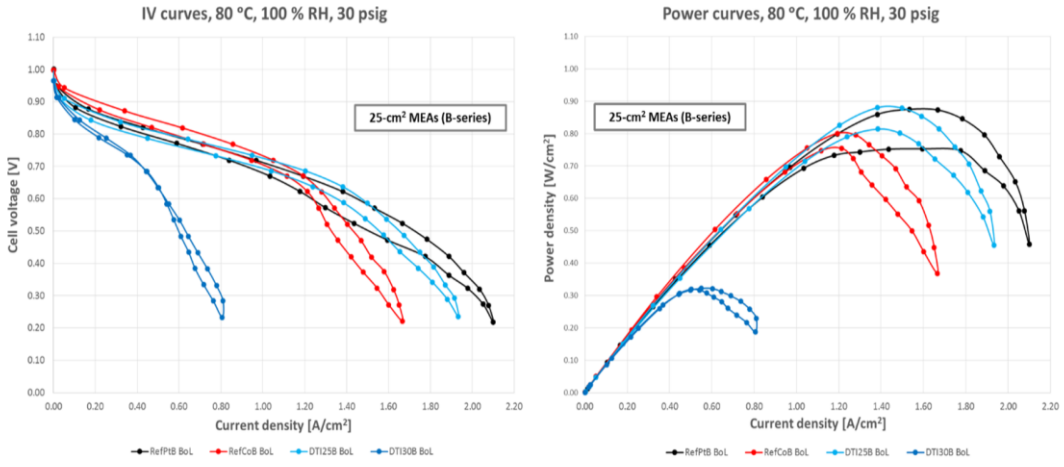

Figure 7. IV curved (left) and power curves (right) for 25 cm^2 MEAs with Pt_xCo/C cathode and a reference MEA with Pt/C cathode.

1.5.5. Alternative supports, benchmarking and Protocols and others

Alternative supports were developed based on carbon and non-carbon materials. Platinized catalysts were prepared and evaluated in lab and in industrial cells. In addition, incorporation of a radical scavenger e.g. SnO_2 into the electrode was found to for improved MEA durability is among the approaches that will be pursued.

In addition, benchmarking and protocols of activity and stability are established for selected commercial catalysts (Pt/C from Johnson Matthey and Pt_xCo/C from Tanaka).

Non-precious metal catalysts are fabricated on a gram scale. Lab evaluation shows immunity towards phosphates and initial test on the HT-PEM cell is performed. Finally technical and economic feasibility of the alloy catalysts and their fabrication processes are evaluated.

1.5.6. Dessimination of the results

- 23 peer reviewed journal papers
- 3 monographs (book chapters)
- 26 oral presentations and posters in international conferences
- 2 European patent applications

- one joint conference organized

1.6 Utilization of project results

The results and learnings for DPS has been an important step for the commercialization of HTPEM. It has resulted in price reduction due to the lower loading of Pt and thus more customers. It is expected that more partners of DPS will have commercial system ready for the market in the near future. In addition the newly synthesized platinum-rare earth metal catalysts, which has eventually achieved a scale of up to 10 grams, will be explored by DPS for technological application in HT-PEMFCs.

The industrial partner EWII has gained a lot of insight into the production of high-performance LT-PEMFC MEAs with the innovative materials developed in the project. Particularly the PtxCo/C catalysts, which DTI is able to produce on a relevant commercial scale, are interesting. Moreover, the smart incorporation of a radical scavenger (SnO_2) into the electrode for improved MEA durability is among the approaches that will be pursued.

DTI is aiming towards utilization of the developed catalysts in uDMFCs for hearing aids. The first product version of these hearing aids will be on the market next year, and future generations requiring higher power output will see the integration of the alloy catalysts. Furthermore, the catalysts have been made available for purchase, initially in amounts smaller than 100 g. The goal is to automate the process further, to bring down the costs and produce the amounts required by DPS and EWII.

DTU Energy has received internal fund of DTU POC (proof of concept) for up-scale preparation and optimization of the methods and materials of platinum-rare earth alloy nanoparticles. Based on the processes patented by DTU Energy, a spinout company is under consideration. The consortium, as whole, will likely further exploit the results within the e.g. EUDP program.

1.7 Project conclusion and perspective

The project addresses catalyst issues of polymer fuel cells from synthesis of novel supports and alloy catalysts, up-scaled fabrication to fuel cell applications. The improved performance of alloy catalysts based on platinum and transitional metals has been clearly demonstrated. The platinum-lanthanide alloy catalysts are chemically synthesized on a gram scale. Utilization of these materials is preliminarily explored for electrode manufacturing and fuel cell tests. These results will be further exploited in commercial fuel cell technologies, likely within the same consortium.

Annexes

Annex 1. Publication list

A). Peer reviewed papers on international journals

1. T. Søndergaard, L. N. Cleemann, L. Zhong, H. Becker, T. Steenberg, H. A. Hjuler, L. Seerup, Q. Li, J. O. Jensen, Catalyst Degradation Under Potential Cycling as an Accelerated Stress Test for PBI-Based High-Temperature PEM Fuel Cells - Effect of Humidification, Electrocatalysis, 9 (2018), pp 302–313
2. 57Fe-Mössbauer spectroscopy and electrochemical activities of graphitic layer encapsulated iron electrocatalysts for the oxygen reduction reaction. L.J. Zhong, C. Frandsen, S. Mørup, Y. Hu, C. Pan, L.N. Cleemann, J.O. Jensen, Q.F.Li, Applied Catalysis B: Environmental, 221 (2018), p. 406-412.
3. Encapsulated iron-based oxygen reduction electrocatalysts by high pressure pyrolysis. L.J. Zhong, Y. Hu, L.N. Cleemann, C. Pan, J. Svaerke, J.O. Jensen, Q.F. Li, International Journal of Hydrogen Energy, 42 (2017), p. 22887-22896.
4. Low-cost graphite as durable support for Pt-based cathode electrocatalysts for proton exchange membrane based fuel cells, Muralidhar Chourashiya, Steffen Vindt, Amado Andrés Velázquez Palenzuela Christoffer Mølleskov Pedersen, Christian Kallesøe and Shuang Ma Andersen, Inter. J Hydrogen Energy, 2018, accepted

5. Zoom in Catalyst/Ionomer Interface in Polymer Electrolyte Membrane Fuel Cell Electrodes: Impact of Catalyst/Ionomer Dispersion Media/Solvent, ACS Appl. Mater. Interfaces, 2018, accepted.

6. An opinion on catalyst degradation mechanisms during catalyst support focused accelerated stress test (AST) for proton exchange membrane fuel cells (PEMFCs), R. Sharma & S. M. Andersen, Appl. Cat. B, 239 (2018), 636-643.

7. Quantification on degradation mechanisms of polymer electrolyte membrane fuel cell catalyst layers during accelerated stress test, R. Sharma & S. M. Andersen, ACS Catalysis, 2018, 8 (4), pp 3424–3434.

8. M. G. Poulsen, M. J. Larsen, S. M. Andersen: Improved durability of proton exchange membrane fuel cells by introducing Sn (IV) oxide into electrodes using an ion exchange method; Journal of Power Sources 343 (2017) pp. 174-182

9. Serguei Chiriaev, Nis Dam Madsen, Horst-Günter Rubahn and Shuang Ma Andersen, Helium Ion Microscopy of Proton Exchange Membrane Fuel Cell Electrode Structures, AIMS Materials Science, 4 (2017), 1289-1304.

10. Electrode performance based on silicon carbide supported platinum catalyst in proton exchange membrane fuel cells, S.M. Andersen & M.J. Larsen, J. Electroanal. Chem., 791 (2017) 175–184.

11. Interface Contribution to the Electrode Performance of Proton Exchange Membrane Fuel Cells – Impact of the Ionomer Content, S.M. Andersen & L. Grahl-Madsen, Int. J. Hydrogen Energy 41 (2016) 1892-1901.

12. The importance of ion selectivity of perfluorinated sulfonic acid membrane for the performance of proton exchange membrane fuel cells, S.M. Andersen, J. Fuel Cell Sci. Tec. (2016), 061010-1 – 061016-7.

13. Nano carbon supported platinum catalyst interaction behavior with perfluorosulfonic acid ionomer and their interface structures, S.M. Andersen, Appl. Catal. B Environ. 181 (2016) 146–155.

14. Graphene layer encapsulated metal nanoparticles as a new type of non-precious metal catalysts for oxygen reduction. Y. Hu, L.J. Zhong, J.O. Jensen, Q.F. Li, Asia-Pacific Journal of Chemical Engineering, 11 (2016), p.382-385.

15. Platinum Iron Intermetallic Nanoparticles Supported on Carbon Formed In Situ by High-Pressure Pyrolysis for Efficient Oxygen Reduction. Y. Hu, J.O. Jensen, W. Zhang, L.N. Cleemann, C. Pan, Chao; Q.F. Li, ChemCatChem, 8 (2016), p. 3131-3136.

16. Immunity of the Fe-N-C catalysts to electrolyte adsorption: phosphate but not perchloric anions, Y. Hu, J.O. Jensen, C. Pan, L.N. Cleemann, I. Shypunov, Q.F. Li, Applied Catalysis B: Environmental, 234 (2018), 357-364

17. Catalyst evaluation for oxygen reduction reaction in concentrated phosphoric acid at elevated temperatures, Y. Hu, Y.L. Jiang, J. O. Jensen, L.N. Cleemann, Q.F. Li, Journal of Power Sources, 375 (2018), 77-81

18. Electrochemical probing into the active sites of graphitic-layer encapsulated iron oxygen reduction reaction electrocatalysts, L.J. Zhong, J.O. Jensen, L. N. Cleemann, C. Pan, Q.F. Li, Science Bulletin, 63 (2018) 24-30

19. Scalable synthesis of carbon supported platinum-Lanthanide and rare earth alloys for the oxygen reduction, C. Roy, B.P. Knudsen, C.M. Pedersen, A. Velázquez-Palenzuela, L.H. Christensen, C.D. Damsgaard, I.E.L. Stephens and I. Chorkendorff. ACS Catalysis 2018 8 (3), 2071-2080

20. Long-Term Durability of PBI-Based HT-PEM Fuel Cells: Effect of Operating Parameters, T. Søndergaard, L.N. Cleemann, H. Becker, T. Steenberg. H.A. Hjuler, L. Seerup, Q.F. Li, J.O. Jensen, J. Electrochem. Soc., 165 (2018) F3053-F3062

21. Long-term durability of HT-PEM fuel cells based on thermally cross-linked polybenzimidazole, T. Søndergaard, L. N. Cleemann, H. Becker, D. Aili, T. Steenberg, H. A. Hjuler, L. Seerup, Q. Li, J. O. Jensen, Journal of Power Sources, 342 (2017), 570-578.

22. Trends in Activity and Dissolution on RuO2 under Oxygen Evolution Conditions: Particles versus Well-Defined Extended Surfaces, Claudie Roy, Reshma R. Rao, Kelsey A. Stoerzinger, Jonathan Hwang, Jan Rossmeisl, Ib Chorkendorff, Yang Shao-Horn, and Ifan E. L. Stephens, ACS Energy Letters 2018 3 (9), 2045-2051

23. C. Roy, B. Sebök, S. B. Scott, E. M. Fiordaliso, A. Bodin, S. B. Scott, J. E. Sørensen, A. Bodin, D. B Trimarco, C. D. Damsgaard, P.C.K. Vesborg, O. Hansen, I. E. L. Stephens, J. Kibsgaard, and I. Chorkendorff; "Impact of Size and Lattice Oxygen on Water

Oxidation on NiFeOxHy", Accepted Nature Catalysis (2018).

b). Monographs and book chapters

24. (Book chapter) High-Temperature Polymer Electrolyte Membrane Fuel Cells, Jens Oluf Jensen, David Aili, Yang Hu, Lars N. Cleemann and Qingfeng Li, in Nanocarbons for Energy Applications, ed. by Naotoshi Nakashima, Springer 2018 (in press)
25. (Edited book) High Temperature Polymer Electrolyte Fuel Cells - Approaches, Status and Perspectives, ed. J.O.Jensen, H.A. Hjuler, D. Aili and Q. Li, Springer (2015)
26. (Book chapter) Durability Issues and Status of PBI-Based Fuel Cells. Jakobsen, Mark Tonny Dalsgaard; Jensen, Jens Oluf; Cleemann, Lars Nilausen; Li, Qingfeng, in High Temperature Polymer Electrolyte Membrane Fuel Cells: Approaches, Status, and Perspectives. ed. Qingfeng Li; David Aili; Hans Aage Hjuler; Jens Oluf Jensen. Switzerland, Springer, 2016. p. 487-509.

c). Presentations, posters, abstracts and proceedings at international conferences

27. A platinum-free oxygen reduction catalyst by a one-step pyrolysis process. J.O. Jensen, Y. Hu, Yang; L.J. Zhong, C. Pan, L.N. Cleemann, Q.F. Li, Invited talk, Abstract from 21st World Hydro-gen Energy Conference 2016, Zaragoza, Spain.
28. Approaches to a platinum free oxygen reduction catalyst for PEM fuel cells. J.O. Jensen, Y. Hu, Yang; L.J. Zhong, C. Pan, L.N. Cleemann, Q.F. Li, Invited talk, Abstract from 16th International Symposium on Biomimetic Materials Processing, Nagoya, Japan.
29. Can We Replace Platinum Metals in PEM Fuel Cells and Electrolyzers? J.O. Jensen, Y. Hu, Yang; L.J. Zhong, C. Pan, L.N. Cleemann, Q.F. Li, Invited talk, Abstract from Hydrides as Energy Materials, Aarhus, Denmark.
30. Fuel Cells and Electrolyzers. Recent Progress at DTU Energy and the Role in a Sustainable Society. J.O. Jensen, Y. Hu, Yang; D. Aili, L.J. Zhong, L.N. Cleemann, Q.F. Li, Invited talk, Abstract from International Symposium in Shiinoki Cultural Complex, Kanazawa, Japan.
31. Non-Platinum Oxygen Reduction Catalysts. From Crystalline to Molecular Moieties. J.O. Jensen, Y. Hu, Yang; L.J. Zhong, C. Pan, L.N. Cleemann, Q.F. Li, Invited talk, Abstract from 4th International Workshop on Solution Plasma and Molecular Technology (SPM-4), Pilsen, Czech Republic.
32. Optimization of Catalyst Layer Properties for High Temperature Polymer Fuel Cells. T. Steenberg, H.A. Hjuler, J.O. Jensen, Q.F. Li, oral presentation and abstracts to Electrochemical Society. MA 2016-02, p. 2801, 2016.
33. Supercritical synthesis of carbon-supported PtxNi and PtxCo nanoparticles as oxygen reduction reaction catalysts for PEMFCs. A. Velázquez-Palenzuela, C.M. Pedersen, P. Hernández-Fernández, L.H. Christensen, C. Kallesøe, oral presentation and abstract to 13th European Congress on Cataly-sis (Europacat 2017), Florence, Italy
34. Up-scaling the production of nanoparticulate catalysts with customized properties: Supercritical flow technology. P. Hernández-Fernández, A.K. Baden, A. Velázquez-Palenzuela, C.M. Pedersen, H.J.L. Silva, L.H. Christensen, C. Kallesøe, oral presentation and abstract to 13th European Congress on Catalysis (Europacat 2017), Florence, Italy
35. Strengthen electrode interface structure for proton exchange membrane fuel cells, Shuang Ma Andersen, 7th International Colloids Conference, 18-21 June 2017, Sitges, Spain.
36. Progress on electrode interface structure modification for proton exchange membrane fuel cells, Shuang Ma Andersen, European Congress and Exhibition on advanced materials and processes (EUROMAT2017), 17 – 22 September 2017, Thessaloniki, Greece.
37. Probing the Ionomer/catalyst Layer Interface at PEMFC Cathode, Raghunandan Shama and Shuang Ma Andersen, Electrochemical Science and Technology Conference 2017, 2nd-3rd of November, DTU.
38. Tungsten Carbide Support Materials for the Hydrogen Evolution Reaction Produced by the Self-Propagating High-Temperature Synthesis Method, M.G. Poulsen, A. Gertov, K.R. Nielsen, S.M. Andersen, 1st International Conference on Electrolysis, 12-15 June, Copenhagen, Denmark.
39. Kasper Rode Nielsen, Jesper Schultz Fredsted, Peter Brilner Lund, Laila Grahl-Madsen; Mikkel Juul Larsen, Shuang Ma Andersen, ELECTROCHEMICAL SCIENCE AND TECHNOLOGY CON-FERENCE 2017, 2nd-3rd of November, DTU
40. Investigating the single-step solution combustion method for synthesis of oxide sup-

ported/unsupported Pt/PtOx, as cathode electrocatalysts for PEMFCs, Muralidhar Chourashiya and Shuang Ma Andersen, oral presentation and abstract to 5th International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications, 18-20 July 2018, University of Aveiro, Portugal

41. Accurate determination of catalyst loading on glassy carbon disk and its impact on thin film rotating disk electrode for oxygen reduction reaction, 5th International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications, 18-20 July 2018, University of Aveiro, Portugal
42. Precious metal metallurgy and its impact on renewable energies, Shuang Ma Andersen Raghunandan Sharma and Kasper Rode Nielsen, keynote speaker at 6th International Conference on Metallurgy Technology and Materials, 30-31 May 2018, Xian China
43. Quantification on degradation mechanisms of polymer electrolyte membrane fuel cell catalyst layers during accelerated stress test, R. Sharma and S. M. Andersen, oral presentation and abstract to International Conference On Renewable Energy, 25-27 April 2018, Barcelona Spain
44. Electrochemical Energy Conversion and Functional Materials, S.M Andersen, keynote speaker at International Conference on Solid State Physics, 10-14 Dec 2017, Lahore, Pakistan
45. PROBING THE IONOMER/CATALYST LAYER INTERFACE AT PEMFC CATHODE, R. Sharma and S. M. Andersen, oral presentation and abstract to Danish electrochemical society annual meeting, 2-3 Nov, 2017, DTU
46. HIGHLY REPRODUCIBLE SUBSTRATE-SPECIFIC ACCELERATED STRESS TEST PROTOCOL, S. T. Vindt1, M. G. Poulsen2, S. M. Andersen, poster presentation and abstract to Danish electrochemical society annual meeting, 2-3 Nov, 2017, DTU
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49. The effect of Nafion® on the Performance of PEMFC Catalysts, E. Skou and S. M. Andersen, Poster presentation and abstract to Solid State Proton Conductor – 18, 2016, Oslo, Norway
50. Up-scaling the production of functional nanomaterials with tailored properties using continuous supercritical flow synthesis, Patricia Hernandez-Fernandez, Christoffer M. Pedersen, Hugo J. L. Silva, Ane K. Baden, Leif H. Christensen, Christian Kallesøe, Key Note oral contribution and abstract to AIM 2018 - Advanced Inorganic Materials Green and Unconventional Synthesis Approaches and Functional Assessment, September 2018, Padova, Italy
51. Up-scaling the production of nanomaterials with customized properties using Continuous Supercritical Flow Synthesis, Christian Kallesøe, Patricia Hernández-Fernández, Ane K. Baden, Christoffer M. Pedersen, Hugo J. L. Silva, Leif H. Christensen, Oral presentation and abstract to PREPA12-12th International Symposium, July 2018, Louvain-La-Neuve, Belgium
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d). Patents

53. Process for producing alloy nanoparticles, Yang Hu, Qingfeng Li, Jens Oluf Jensen, Lars Nilausen Cleemann, Benedikt Axel Brandes, European patent application no.: 18197633.3 (filed 28 September 2018)
54. Process for producing metal alloy nanoparticles, Qingfeng Li, Jens Oluf Jensen, Lars Nilausen Cleemann, Benedikt Axel Brandes, Yang Hu, European patent application no.: 18197633.3 (filed 28 September 2018)

Annex 2. Relevant links

The project homepage https://ipro.ecs.dtu.dk/upcat/