Editorial for the Virtual Special Issue of Journal of Power Sources “Low temperature fuel cells and electrolysers” - Science and engineering: Let’s play this game hand in hand!

Kateryna Artyushkova, Tatyana Reshetenko, Christina Roth, Carlo Santoro, Alexey Serov, Johan André, Marian Chatenet

To cite this version:

Kateryna Artyushkova, Tatyana Reshetenko, Christina Roth, Carlo Santoro, Alexey Serov, et al.. Editorial for the Virtual Special Issue of Journal of Power Sources “Low temperature fuel cells and electrolysers” - Science and engineering: Let’s play this game hand in hand!. Journal of Power Sources, 2022, 550 (6), pp.232123. 10.1016/j.jpowsour.2022.232123 . hal-03917973

Editorial for the Virtual Special Issue of Journal of Power Sources "Low temperature fuel cells and electrolysers" - Science and Engineering: let's play this game hand in hand!

Kateryna Artyushkova [1], Tatyana Reshetenko [2], Christina Roth [3], Carlo Santoro [4], Alexey Serov [4], Johan André [6], and Marian Chatenet [7]

[1] Physical Electronics Inc.

[2] Hawai'i Natural Energy Institute, University of Hawaii, Honolulu, HI 96822, USA

[3] University of Bayreuth, Germany

[4] Electrocatalysis and Bioelectrocatalysis Laboratory (EBLab), Department of Materials Science University of Milano-Bicocca, U5, Via Cozzi 5, 20125, Milan (Italy)

[5] Electrification and Energy Infrastructures Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

[6] Air Liquide, 2 rue de Clémencière, BP 15, 38360 Sassenage, France

[7] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, Grenoble INP*, LEPMI, 38000 Grenoble, France

*Institute of Engineering and Management Univ. Grenoble Alpes

Electrochemistry is already and will increasingly be amongst the major drivers of our energetic mix decarbonization, so to fight anthropogenic global warming. The hydrogen economy vector (ideally produced in water electrolysers using renewable electricity and transformed back into electricity in fuel cells), in parallel with the conversion of carbon dioxide and nitrogen gas into value-added products are seen as pillars of the so-called green and sustainable Energy Revolution. The hydrogen technologies presently attract increasing interest, their momentum growing irremediably in Europe, Asia and Americas. In that frame, this Virtual Special Issue (VSI) gathers the latest scientific results of major research laboratories worldwide, all addressing various aspects of electrochemical energy and material conversion processes.

These manuscripts and reviews touch challenging research topics related to materials science, novel synthesis approaches, microscopic and spectroscopic characterization, integration of materials into electrodes, transport phenomena, electron transfer mechanism, electrochemical performance characterization and device operations in low-temperature fuel cells and water electrolysers. The papers further put the emphasis on the development of advanced materials to be employed, with the specific objective to minimize or avoid the use of scarce platinum group metal-based electrocatalysts. Their replacement with more abundant and low cost first raw transition metal materials renders the hydrogen devices more environmental-friendly and cost-attractive. The studies present the latest developments of the world-wide scientific research and are related to materials demonstrating excellent performance equal or above state-of-the-art, when they are measured in laboratory-scale cells. Reaching this level of performance is of course mandatory if one wants to deploy the materials in real conditions (*i.e*. industrial cells). However, it is not sufficient to reach best system performance, and this is where engineering comes into the play in complement to science; this strategy has now become popular in the field, as for example illustrated by the decade-long partnership of the groups of LEPMI (in Grenoble) and LEMTA (in Nancy) with Air Liquide on the field of proton exchange membrane fuel cells (PEMFC). The fundamental aspects developed in labs on real PEMFC stacks/systems having been operated by Air Liquide in the field (real-life) enabled outstanding progresses in terms of PEMFC systems understanding, optimization of their reliability and durability (see for example [1,2,3,4,5,6,7,8,9]), but also led to the discovery of an outstanding class of Pt-based electrocatalysts, containing structural defects [10]. This strategy of coupling the fundamental efforts of labs and industrial developments has also been pursued successfully by Prof. Plamen Atanassov in the last two decades. Plamen's biography is an excellent example of how the combination of thinking in both worlds can push forward basic science to real applications. With this VSI, we aim to celebrate him at the occasion of his 60th birthday, occurring in November 2022. Hereafter, and in complement to the important pieces of scientific research composing this VSI, the importance of industrial engineering aspects and the fruitful and extremely necessary interplay between university and industry is illustrated by a few examples related to proton exchange membrane fuel cells for transportation.

Best power density *vs*. best performance

Considering the example of fuel cell development for mobile applications, nearly all practical studies target to increase the cell power density, whether in terms of volumetric or gravimetric values. In general, the volumetric index primes for ground transportation, when the mass reduction becomes the priority for aeronautical applications. Whatever application is considered, the highest system efficiency should be reached so not to compromise the energy density or specific energy of the whole system, which means that high power density should not necessarily be pursued by any means. The illustrative examples addressed hereafter aim to answer the question "**Are amazing power density figures meaningful?**" and to shed light onto other often omitted or overlooked practical issues.

- **Supplier B is selling off-the shelf stacks with very high power density, way superior to supplier A; in these conditions, is B necessarily better than A?**

As a matter of fact, some figures may be very misleading. A famous stack supplier claims a rated power up to 140 kW, with a specific power density of 4.7 kW/kg, excluding end plate hardware [11]. In that case, the stack mass (net) is announced to be 55 kg. Confronting these figures, one easily calculates that *ca*. 25 kg would be attributed only to clamp the stack, which appears rather surprising (and inefficient) in terms of system engineering. So, although the specific power density of 4.7 kW/kg announced in the datasheet is highly impressive, a more correct value should be considered: 140 kW / 55 kg = 2.55 kW/kg (including end plate hardware), which suggests that one should read between lines.

- **What is or is not considered in the volume or mass of a PEMFC stack?**

As a matter of fact, this example is not unique, and end components are often conveniently removed from the equation when power density figures are announced; one could wonder why. The answer is that the intrinsic performance of the cell matters most. Stacking 50 or 200 cells with the same design and same end components would lead to different power density values for the same cell performance. Moreover, the end component design often aims at relevant engineering so as to be tailored to meet the customer requirements: cost reduction for mass production, weight or volume limit, specific constraints linked to a standard (flammability, electrical insulation), *etc*. As such, one should be careful when looking at volumetric/gravimetric power density values because some stack designs hide tie-rods within the plates (C260 model of Air Liquide [12]), while other models need extra-volume/mass out of the plate section (M240 [13]). This last way to proceed is sometimes a trick to artificially display high performance, or a way to have a design easily compatible with band fastening. In any case and again, it is crucially important to read between lines in the data sheets and have a proper understanding of the real meaning of the performance announced.

- **Peak power is not peak efficiency!**

When a stack developer wants to sell its stack, the power density may correspond to the maximum power the stack can deliver. Whatever its interest, this value may be somewhat different from the peak power the system will be capable to provide in reality (typically ten points of efficiency or more can be found between maximum power and power at maximum efficiency). The latter may be limited by the necessary annex components of the stack within the system: the power converter maximum current, range of air stoichiometry allowable with the blower at given atmospheric conditions, pressure achievable with the compressor at a given efficiency, *etc*. In addition, the peak power the system will be capable to provide in reality may differ from the power density at nominal efficiency at BOL (Beginning-Of-life) and EOL (End-Of-Life). As a result, operating point should be given for some transparency (in terms of V/cell) and for precisely-given operating conditions.

- **Power range and stacking limit**

Starting from an existing 10 kW stack, with a given power density (in kW/L), could one add some cells and reach 40 kW? To some extent, this may be possible, and stack developers usually want to use the same cell design for a wide power range. However, sometimes, fluid ports present the necessary size for the designed power and not more. One way to overcome this hurdle could be to increase operating pressure but this is not always possible and can bring new drawbacks such as gas tightness, efficiency loss, inadequacy of the air compressor, …. So, to keep it short, make sure that maximum cell count will fit your requirement, as modularity is not granted.

- **Embodied energy, cost and material scarcity**

If you looked at fuel cells for environmental reasons or if you simply want your business to be sustainable on the long term, the following matters. To reduce consumption, the lighter the better! This is true, but what if embodied energy has grown tremendously? For example, titanium can be preferred to stainless steel for use as bipolar plate material, owing to its high corrosion resistance and low density (despite limitations for flow-field formation - titanium has a low elongation limit and is hard to machine). However, one should know that producing 1 kg of titanium requires 44 kWh [14], ca. 2.8 times more than for the same amount of stainless steel (ca. 15.8 kWh/kg [15]). Thanks to its low density, volumetric comparison leads however to a lower energy consumption penalty ca. 60% for titanium.

As another example, expanded graphite flakes can represent a good candidate for bipolar plate production. Using graphite has the advantage not to pressure the metal markets, many metals, especially alloying elements such as nickel or chromium, becoming critical in terms of availability/cost. The results in terms of gravimetric power density will be very close to titanium. After Membrane Electrode Assembly (MEA) end-of-life, plates could be used again, or if mechanically damaged, recycled to enrich the carbon content of steels for hardening.

Another trick can be the use of extremely low plate thickness (50 to 75 µm sheet), which would dramatically increase gravimetric power density. Although a nice idea in theory, as this will save weight and metallic resources, it can be practically awkward and requires very high-quality control to avoid that a single inclusion compromises the operation of a complete stack.

- **MEA trade-off**

Many different MEA formulations are now accessible on the market with different active layers, catalyst loadings, membrane thickness, *etc*. Each parameter can influence, cost, initial performance, and lifetime. Can we generalize that the more kW/L, the better? Not that simple! Over the last decades, membrane thickness has been decreasing impressively, down to 8 µm on some stacks. This leads to lower ohmic drop and better water management (self-humidification of cathode being somewhat possible with hydrogen recirculation). To some extent, no compromise was done with lifetime thanks to mechanical reinforcement, but the highest power density achieved with one MEA may also be associated to poor tolerance to pressure difference between anode and cathode, quality issues (pinholes present in the MEA at BOL, and faster degradation), which are hard to track and can prematurely compromise the real operation. As an answer, the art of MEA engineering is to tailor the components to properly address the customer needs for a whole product performance on the long term, preventing quality issues or abnormally fast performance decay.

- **Operating conditions matter**

Sometimes, datasheets promise many kW/L thanks to a large power density (W/cm²), but this power may be reached only in operating conditions that come with their drawbacks, e.g. a low cell temperature (e.g. 60-70°C), which renders the cell cooling complex and requires large heat exchanger, low delta *T* (bigger cooling pump), high air stoichiometry and/or pressure (bigger blower) with a poor tolerance to anode/cathode delta *P*. At the scale of the system, this may not be a winning strategy.

How many kW/L should a PEMFC stack reach to be competitive? A case study

Industrial manufacturers should be fully transparent on this topic, as it is critical in the decision-making process of end-users. In June 2018, a technology assessment of the 2017 Toyota Mirai was led by Argonne National Laboratory [16]. Any stack developer can find many operating parameters in this report and publish a polarization curve of its own stack, and compare the performance to Mirai stack. Only the stack operating temperature is not given (assumed to be 80°C), while MEA active area should be 237 cm² according to James *et al.*[17]

In 2019, Axane developed for a car manufacturer a new liquid-cooled fuel cell stack based on metallic bipolar plates. In order to assess its performance in operating conditions it was compared to data provided in ANL's report. BOL operating points of the 2019's Axane stack correspond to red dots in Figure 1, based on MEA formulation available three years earlier, as compared to the Toyota Mirai data. The cell pitch was 1.15 mm, selected to be an acceptable trade-off between delta *P* tolerance and power density. Smaller would be possible on demand, and since 2019, MEA science made some progress to get more power density. Overall, the performance of this M-240 stack from AXANE are summarized in Table 1 and provide an apple-to-apple comparison of the performances

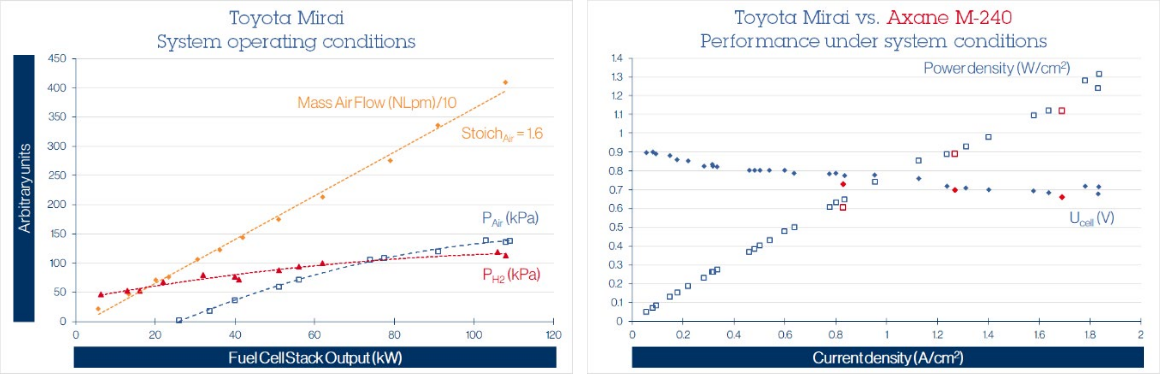

Figure 1 : Performance of the Toyota Mirai 2017 PEMFC stack (right) and its comparison to the Axane M-240 stack (red data points) (right).

*Table 1 : Some data regarding Axane stack power density based on today BOL performance (bold) and forecast. * excluding end components at 0.65V, 1barg, 75°C St 2,0 wet air ** excluding end components at max power (~0,5V, 1,2 barg, 75°C St 2,2 wet air)*

	current machined graphite C260 cell	next gen. machined graphite C260 cell	expanded graphite cell	New composite cell with 0.2mm wall thickness - based on M240 design	**M240 precoated hydroformed stainless steel cell**	M240 stainless steel cell from 75µm coil	M240 75µm titanium coil assumption
nominal volumetric power density (kW/L)*	**1,69**	2,18	2,64	4,24	**4,98**	5,20	5,72
peak volumetric power density (kW/L)**	**2,40**	3,08	3,74	6,01	**7,05**	7,37	8,11
nominal massic power density (kW/kg)*	**1,59**	2,22	3,05	5,30	**3,67**	4,68	7,41
peak massic power density (kW/kg)**	**2,26**	3,14	4,31	7,50	**5,19**	6,62	10,50

These examples all show that clarity and attention to the realistic operating conditions should always drive our manner of presenting technical data.

With this illustration of the paradigm of comparing performances of fuel cells (which is also valid for water electrolysers), enjoy your reading of the impressive collection of papers of this VSI of Journal of Power Sources providing the science on “Low temperature fuel cells and electrolysers”!

References

---

[1] E. Guilminot, A. Corcella, F. Charlot, F. Maillard, M. Chatenet, Detection of Ptz+ ions and Pt nanoparticles into the membrane of a PEM fuel cell, J. Electrochem. Soc. 154 (2007) B96-B105; http://dx.doi.org/10.1149/1.2388863

[2] E. Guilminot, A. Corcella, M. Chatenet, F. Maillard, F. Charlot, G. Berthomé, C. Iojoiu, J.-Y. Sanchez, E. Rossinot, E. Claude, Membrane and active layer degradation upon Proton Exchange Membrane Fuel Cell steady-state operation – part I: platinum dissolution and redistribution within the Membrane Electrode Assembly, J. Electrochem. Soc. 154 (2007) B1106-B1114; http://dx.doi.org/10.1149/1.2775218

[3] C. Iojoiu, E. Guilminot, F. Maillard, M. Chatenet, J.-Y. Sanchez, E. Claude, E. Rossinot, Membrane and active layer degradation upon Proton Exchange Membrane Fuel Cell steady-state operation – part II: effect of platinum on membrane degradation, J. Electrochem. Soc. 154 (2007) B1115-B1120; http://dx.doi.org/10.1149/1.27785282

[4] L. Dubau, F. Maillard, M. Chatenet, Laure Guetaz, J. André, E. Rossinot, Durability of Pt3Co/C cathodes in a 16 cells PEMFC stack: macro/microstructural changes and degradation mechanisms, J. Electrochem. Soc. 157 (2010) B1887-B1895; http://dx.doi.org/10.1149/1.3485104

[5] L. Dubau, F. Maillard, M. Chatenet, J. André, E. Rossinot, Nanoscale compositional changes and modification of the surface reactivity of Pt3Co/C nanoparticles during PEMFC operation, Electrochim. Acta 56 (2010) 776–783; http://dx.doi.org/10.1016/j.electacta.2010.09.038

[6] L. Dubau, J. Durst, F. Maillard, L. Guétaz, M. Chatenet, J. André, E. Rossinot, Further insights into the durability of Pt3Co/C electrocatalysts: Formation of “hollow” Pt nanoparticles induced by the Kirkendall effect, Electrochim. Acta 56 (2011) 10658-10667; http://dx.doi.org/10.1016/j.electacta.2011.03.073

[7] L. Dubau, J. Durst, F.Maillard, M. Chatenet, J. André, E. Rossinot, Heterogeneities of Aging within a PEMFC MEA, Fuel Cells 12 (2012) 188-198; http://dx.doi.org10.1002/fuce.201100073

[8] L. Dubau, M. Lopez-Haro, L. Castanheira, J. Durst, M. Chatenet, P. Bayle-Guillemaud, L. Guétaz, N. Caqué, E. Rossinot, F. Maillard, Probing the structure, the composition and the ORR activity of Pt3Co/C nanocrystallites during a 3422 h PEMFC ageing test, Appl. Catal. B 142-143 (2013) 801-808; http://dx.doi.org/10.1016/j.apcatb.2013.06.011

[9] L. Dubau, L. Castanheira, F. Maillard, M. Chatenet, O. Lottin, G. Maranzana, J. Dillet, J.-C. Perrin, E. Moukheiber, A. ElKaddouri, G. deMoor, C. Bas, L. Flandin, N. Caqué, Durability of membrane-electrode assembly under proton-exchange membrane fuel cell operation: from materials degradation to local heterogeneities of aging and possible mitigation strategies, Wiley Interdisciplinary Rev. Energ. Environ. 3 (2014) 540-560; http://dx.doi.org/10.1002/wene.113

[10] L. Dubau, M. Lopez-Haro, J. Durst, L. Guétaz, P. Bayle-Guillemaud, M. Chatenet, F. Maillard, Beyond conventional electrocatalysts: hollow nanoparticles for improved and sustainable oxygen reduction reaction activity, J. Mater. Chem. A, 2 (2014), 18497-18507; http://dx.doi.org/10.1039/c4ta03975k

[11] https://www.ballard.com/docs/default-source/spec-sheets/fcgen-hps.pdf?sfvrsn=704ddd80_4, consulted on July 22nd, 2022

[12] https://energies.airliquide.com/sites/abt_ne/files/2021/03/08/axane_datasheet_c-stack260_05.22_sd.pdf, consulted on July 22nd, 2022

[13] https://energies.airliquide.com/sites/abt_ne/files/2020/12/07/axane_datasheet_m-stack240_06.20_sd.pdf, consulted on July 22nd, 2022

[14] https://lelementarium.fr/element-fiche/titane-2/, consulted of July 22nd, 2022

[15] Hammond (2011), “Embodied Carbon. The Inventory of Carbon and Energy (ICE)”, G. Hammond, C. Jones, 2011, BSRIA, ISBN: 978-0-86022-703-8

[16] Report # ANL/ESD-18/12, Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai Energy Systems Division (2017).

[17] B. James, NREL , “Fuel Cell Systems Analysis”, 2017 DOE FCTO AMR, Project ID# FC163