

Mapping Transition Metal-Nitrogen-Carbon Catalysts Performance on the Critical Descriptors Diagram

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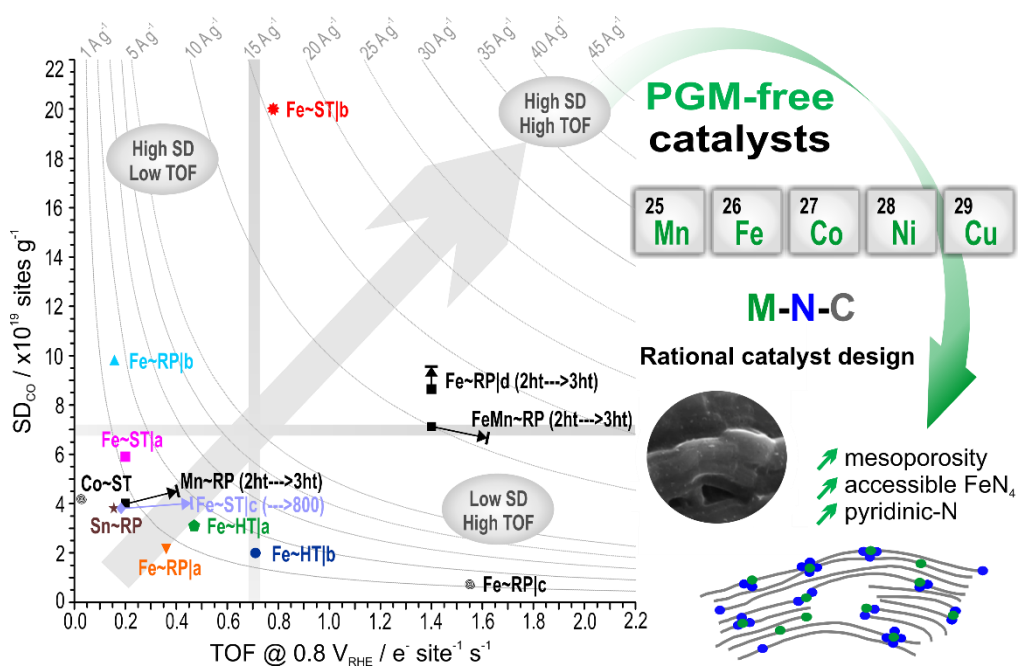
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Graphical abstract



Highlights

- Site density vs. ORR turn-over frequency for PGM-free catalysts from the literature.
- Rational catalyst design: + mesoporosity, + accessible FeN₄ centers, + pyridinic-N.
- Crucial role of the precursors and synthesis method in catalysts formation.

Abstract

PGM-free electrocatalysts, and in particular transition metal-nitrogen-carbon (M-N-C) catalysts are becoming interesting candidates as cheap alternatives to Pt-based catalysts for the oxygen reduction reaction (ORR) in polymer electrolyte fuel cells (PEFC). Unified activity-stability correlations are needed in order to provide practical guidelines for a rational catalyst design. A discussion of different characterization techniques for studying possible activity descriptors is presented, with a specific focus on active-site density (*SD*) and turn-over frequency (*TOF*). These descriptors will be associated to the morphology of the various M-N-C electrocatalysts investigated in the recent literature. The underlined correlation for this class of PGM-free electrocatalysts offers important insights required for the development of the next-generation of catalytic materials with enhanced stability, that can solve the main activity and durability barriers needed for the replacement of Pt-based counterparts.

Key words: platinum group metal (PGM)-free electrocatalysts; transition metal-nitrogen-carbon (M-N-C) catalysts; activity descriptors; gravimetric active-site density (*SD*); turn-over frequency (*TOF*).

Introduction

Although polymer electrolyte fuel cells (PEFCs) are recognized worldwide as pollution-free and high-performance devices, their mass commercialization is still a long way off [1–4],

mostly because they are still an expensive technology. Almost 50% of the cost, in fact, is attributable to Pt-based catalysts [5]. Platinum group metals (PGM) on earth are scarce and expensive. A high amount of Pt is necessary to favor the oxygen reduction reaction (ORR), which is a well-known sluggish electrode reaction [6]. To overcome such a bottleneck, transition metal (Fe,Co)/nitrogen-doped carbon structures (M-N-C materials) have been widely investigated in the last decades due to their great electrocatalytic activity for ORR [7–15]. M-C-C materials have also extraordinary tolerance to alcohols, a beneficial property for direct alcohols fuel cells (DAFCs) [16,17]. Notwithstanding all the research efforts, these materials still suffer from low activity compared to PGM catalysts, and stability is still an issue [18–23]. As stated more than ten years ago by Gasteiger and Markovic [1], only via rational catalyst design routes we can push the overall intrinsic activity of M-N-C catalysts close to that of Pt-based materials.

According to the targets established by the U.S. Department of Energy (DOE), the specific activity of PGM-free catalysts implemented in a H₂/O₂ PEFC operating at 1 bar at 0.9 V_{iR-free} is expected to be 44 mA cm⁻² [5], to be competitive compared to PGM electrocatalysts. This activity target is equivalent to the PGM activity target calculated from the product of mass activity, 440 mA mg_{Pt}⁻¹, and the target Pt cathode loading of 0.100 mg_{Pt} cm⁻² [5]. The two best activities recorded so far with Fe-N-C catalysts reach only 75% and 66% of this target (33 mA cm⁻² with a catalyst prepared from zeolitic imidazolate framework (ZIF) via chemical vapor deposition (CVD) [24] and 29 mA cm⁻² with a catalyst prepared from ZIF via reactive polymerization [25], the latter reached within the ElectroCat Consortium [26]).

Active Site Density and Turn-Over Frequency: Two Critical Descriptors

To better understand the activity of PGM-free catalysts, scientists disclosed several descriptors to identify the nature of the active sites towards ORR, which is still under debate. In fact, not only Fe-N₄ active sites, but also Fe-moieties and Fe-free moieties can contribute to the ORR [13]. Among them, the most typical descriptors debated in the literature are structural ones, usually determined by N₂ sorption measurements, ⁵⁷Fe Mössbauer spectroscopy, X-ray photoelectron spectroscopy (XPS), X-ray absorption near-edge spectroscopy (XANES), X-ray photoelectron and mass spectroscopy (EXAFS), neutron

activation analysis, and with the help of density functional theory (DFT) calculations [19,27–30], and reactivity ones, such as redox potential of the FeN_x or CoN_x active centers, adsorption energy of intermediate products and work function [31–37]).

Nowadays, two reactivity descriptors, the active metal gravimetric site density, SD [$\text{site g}_{\text{cat}}^{-1}$], and the catalytic turn-over frequency, TOF [$\text{electron site}^{-1} \text{s}^{-1}$], are becoming predominant since their combination discloses the catalysts' intrinsic kinetic activity at a selected potential, $J_{\text{kin, mass}}$ [A g^{-1}], as clearly explained by Zagal et al. [38]. Thus, the evaluation of TOF and SD is recognized as one of the most accurate comparisons among different catalysts [39].

The SD can be measured by *ex situ* cryo CO chemisorption or *in situ* adsorption of NO_2^- [38]. Interestingly, by observing SD values of some catalysts reported in **Table 1**, measured on the same catalysts by CO chemisorption and NO_2^- adsorption, the resulting SD_{NO_2} is always smaller compared to the SD_{CO} . The reason lies in the ability of the CO molecules to easily access the porosity of the catalysts, especially the microporosity, thus reaching more active sites. Primbs et al. [40] correlated the gaseous CO uptake on the basis of SD_{CO} calculation with the specific surface, pore structure, and bulk weight Fe content. Whereas the correlation was weaker with SD_{NO_2} . In fact, against a set of four catalysts with different physico-chemical characteristics (**Table 1**: Fe~ST|a [40], Fe~RP|a [40,41]; Fe~HT|a [40,42]; Fe~HT|b [40,43]), the larger difference between the two values of SD belongs to the catalyst with the largest specific volume of micropores, and the smallest specific volume of mesopores (Fe~ST|a). This is a clear sign that active sites present in micropores are accessible only by probe CO molecules, while they are hidden from NO_2^- .

Recently, Kumar et al. [44] demonstrated the NO_2^- adsorption method can provide SD values, which include not only contributions from the FeN_4 active sites, but also from other species, such as Fe_2O_3 . The authors performed a deep study on fresh/aged $\text{Fe}_{0.5}/\text{NC}$ and $\text{Fe}_2\text{O}_3/\text{NC}$ catalysts, calculating that the $\text{Fe}_2\text{O}_3/\text{NC}$ catalyst displayed a slightly higher SD but lower TOF compared to the more active fresh $\text{Fe}_{0.5}/\text{NC}$, being rich of only FeN_x sites (**Tables 1 and 2** [44]). This is a demonstration that SD_{NO_2} measurements are sensitive to the presence of FeO species. The authors also evaluated the SD/TOF values before/after a series of

accelerated stress tests (AST) on the Fe_{0.5}/NC catalyst. AST in presence of oxygen under potential cycling (AST-OPC: 0.6-1.0 V vs RHE) caused a large decrease of the mass activity of the aged Fe_{0.5}/NC, mainly due to carbon corrosion. This was accompanied by an unexpected +40% of the *SD* value and -50% of the *TOF* value compared to the fresh Fe_{0.5}/NC (**Table 1**, [44]). A combination of electrochemical experiments and chemical/morphological characterizations on the aged catalyst pointed out that more Fe atoms were exposed on the surface because of the presence of reactive oxygen species (ROS) which enhanced carbon corrosion. These Fe atoms were no longer solely in the form of FeN_x sites, but with a prevalence of FeO, due to the re-precipitation of Fe cations reacting with ROS to form Fe oxides [44]. Moreover, carbon corrosion was preferentially on structurally disordered domains, leaving the more graphitic domains almost unaffected [45]. This work also pointed out the effects of ageing on the change of chemical-morphological structure of Fe-N-C catalysts. The shift of Fe species from FeN_x to FeO combined with the preferential corrosion of disordered carbon was labelled as ROS-induced carbon corrosion [44]. Furthermore, other research on deactivation of Fe-N-C catalysts [33] demonstrated that the presence of H₂O₂ leaves FeN_x sites untouched but enhances the reversible oxidation of the carbon surface. Consequently, the ORR activity is reduced and the *TOF* decreased via weakened O₂ binding. In fact, catalysts containing only Fe particles encapsulated in a graphitic shell do not suffer deactivation (no iron exposed on the surface), but are intrinsically less active. Therefore, the chemical-morphological characterization of the catalysts is of utmost importance to better understand the origin of the activity, and to determine the correct values of *SD* and *TOF* for a proper comparison of different catalytic materials, at fresh and aged states. Moreover, the mismatching *SD* and *TOF* values, determined by the NO₂⁻ adsorption method, compared to mass activity values unravel the sensitivity of the analysis to both FeN_x and FeO species, by highlighting the complexity and plurality of the degradation mechanisms of Fe-N-C catalysts.

The Case of Heat-Treated Transition Metal-Nitrogen-Carbon Catalysts

Most of the PGM-free catalysts are prepared by mixing reactants and pyrolyzing them under specific conditions of temperature, atmosphere, and time. The pyrolysis leads to a series of chemical and morphological transformations with the formation of active sites, that nature of which is still under debate [13]. However, these materials exhibit much

higher activity and stability compared to intact (not pyrolyzed) PGM-free catalysts [38,46]. A relevant difference between Fe-N-C materials and intact macrocyclic FeN₄ complexes is the difference in the inner N₄ coordination around the metal center. For Fe-N-C materials, there is evidence of pyridinic ligation fused with graphite layers whereas for the majority of intact MN₄ metal complexes they feature pyrrolic ligation. These differences have been characterized in detail by ⁵⁷Fe Mössbauer spectra, XPS and atomic-resolution TEM of both intact and pyrolyzed materials. For example, Marshall-Roth et al. [47] have recently reported the preparation of Fe complexes based on phenanthroline hexaazamacrocyclic, (phen₂N₂)Fe, that feature a pyridinic N₄ coordination environment around Fe, similar to that of Fe-N-C materials with high *TOF* (1.8 s⁻¹) for ORR in acid.

The pyrolysis and the nature of precursors used for the synthesis of Fe-N-C materials lead to a plurality of Fe-based active sites: Fe-N₄, Fe-N₃, Fe-N₂, Fe-N₂₊₂, Fe-N₄₊₁, N-Fe-N₂₊₂, Fe-N_xC_{4-x}, Fe-nanoparticles (α -Fe and γ -Fe), Fe-nitrides and Fe-carbides, usually termed as Fe-containing moieties active sites [13]. All of these sites can be available for ORR, depending on their location: in-plane and out-of-the-plane, on the edge of carbon crystallites, encapsulated in the carbon matrix, etc. [13,44]. Each of them is contributing to the overall activity of the catalyst, either by acting on the *TOF* (the higher the *TOF*, the more active the site is) or the *SD* (the higher the *SD*, the more the active sites are).

Thus, the critical rational design question is: Is it more advantageous to synthesize catalysts with a higher *TOF*, or to aim synthesis efforts at achieving a higher *SD*?

Let us observe **Figure 1**, showing the *SD*_{CO} versus *TOF* map of Fe-based catalysts derived from different precursors. The values are taken from different publications, at equal conditions on rotating(-ring) disk electrode (RDE or RRDE) at 0.8 V_{RHE} and *SD* measured by *ex-situ* CO chemisorption. **Table 1** lists the punctual values depicted in the figure. **Table 2** lists a brief summary on the synthesis processes used to prepare these catalysts. The materials have been subdivided into three main “families” of catalysts depending on the nature of the precursors used, and the type of synthesis:

- Catalysts derived from ZIF precursors via soft-templating (M~ST: Fe~ST|a [40], Fe~ST|b [24]); Fe~ST|c [48], Co~ST [49,50];
- Catalysts derived from polyaniline (PANI) or diaminonaphthalene precursors via reactive polymerization (M~RP: Fe~RP|a [40,41]; Fe~RP|b [49], Fe~RP|c [51], Fe~RP|d [52]49, Mn~RP[52], FeMn~RP[52], Sn~RP [49];
- Catalysts derived from organic precursors and SiO₂ via hard-templating (M~HT: Fe~HT|a [40,42]; Fe~HT|b [40,43], the latter a commercial catalyst from Pajarito Powder [43]).

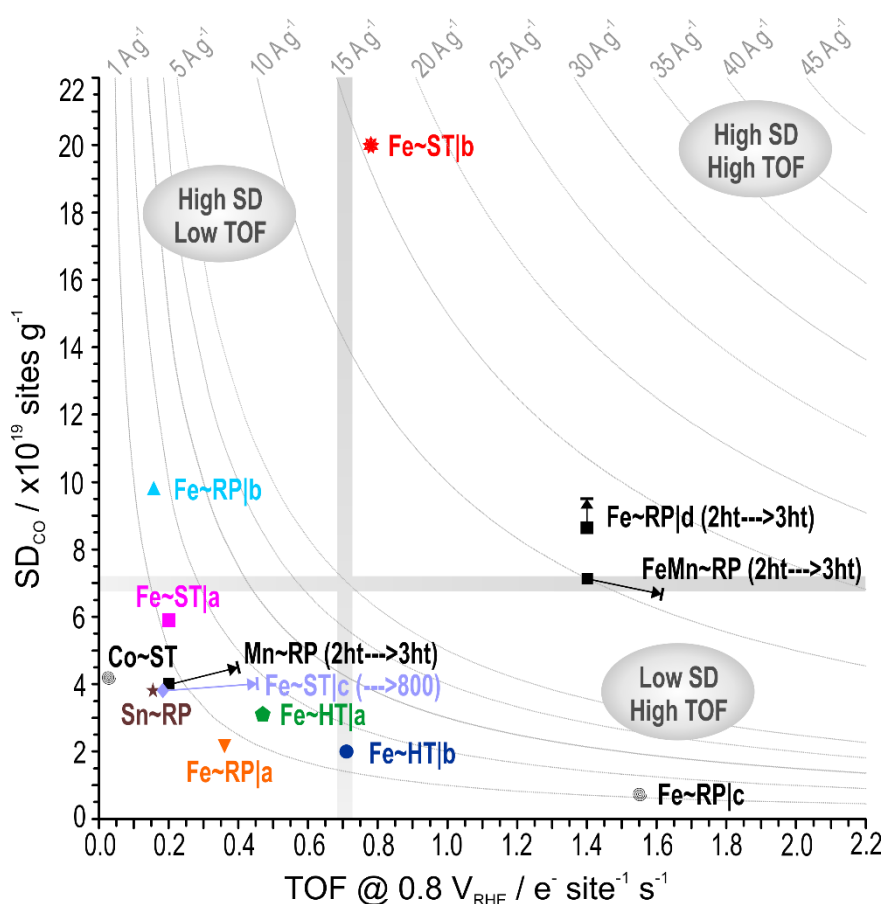


Figure 1. Map of gravimetric active-site density vs ORR turn-over frequency for a series of PGM-free catalysts from the literature (measurements performed in RDE or RRDE). Reactivity map resulting from *SD* measured by CO chemisorption. Hyperbolic iso-activity curves in A g⁻¹ at 0.8 V_{RHE} are also reported. Catalysts abbreviations: M~ST derived from soft-templating; M~RP derived from reactive polymerization (M~RP|2ht→3ht → reactive

polymerization followed by 2 or 3 heat treatments); M~HT derived from hard-templating (for synthesis methods, see **Table 2**).

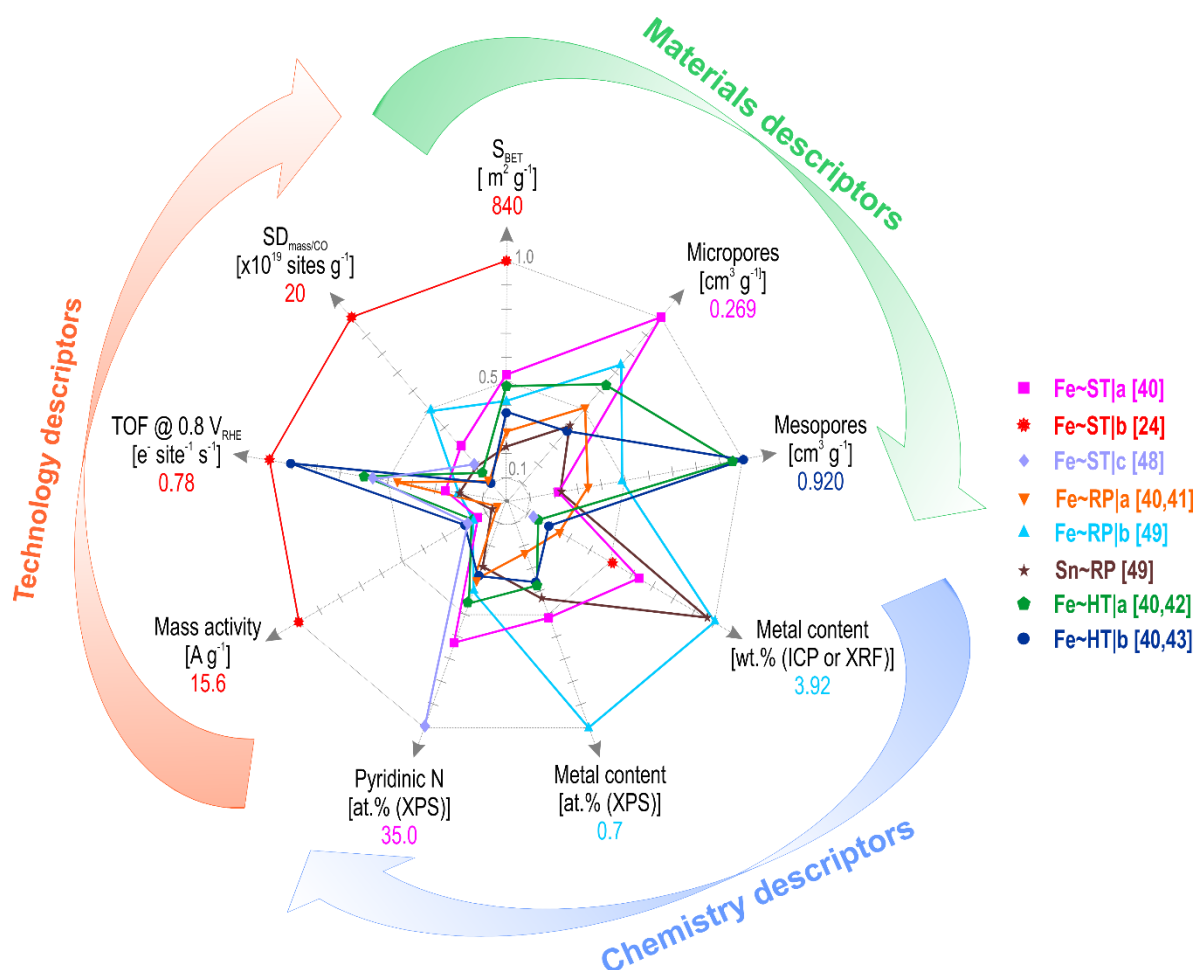


Figure 2. Radar plot of the colored catalysts in **Figure 1** for a relative comparison of the main physico-chemical data (exact values listed in **Table 1**). The three main descriptor categories are highlighted. Catalysts abbreviations: M~ST derived from soft-templating; M~RP derived from reactive polymerization; M~HT derived from hard-templating Data taken from the literature.

By subdividing the map into four quadrants, from low to high values of *SD* and *TOF*, we observe different behaviors. The three catalysts derived from the soft templating of ZIF, Fe~ST|a, Fe~ST|c, and Co~ST, lie in the lower quadrant, with low *TOF* and *SD* values. The mass activity is extremely low, as well. Apparently, the amount of active sites is similar, but the activity of the Co-based catalyst is negligible. Interestingly, when Fe~ST|c is further heat-treated at 800 °C under CO atmosphere, both the mass activity and *TOF* results increased by about 60%, while the *SD* increased only slightly (**Table 1**). The different rate of variation of *TOF* and *SD* point towards the formation of more intrinsic active sites rather than the formation of new active sites, such as a different thermally-induced FeN_x site distribution [48]. Looking at the radar plot, **Figure 2**, the Fe~ST|a catalyst has the highest value of micropores and pyridinic-N, which are notoriously two characteristics known to favor the formation of active sites [27,53].

Interestingly, the Fe~ST|b catalyst, which is derived from a nanosized ZIF-8, lies in the upper quadrant, with a *TOF* value comparable to others in the literature, and an extremely high *SD* value, equivalent to the 47% Pt/C catalysts [39]. High values of *SD* are extremely beneficial in MEA testing, especially at high current densities where transport limitations dominate [12,19,54,55]. In fact, the Fe~ST|b catalyst tested on H₂/O₂ PEFC, reached an activity of 33 mA cm⁻² at 0.90 V_{iR-free} [24]. This exceptional result, which pushes this catalyst to the top-center of the map, can be ascribed to its morphological characteristics. In fact, this catalyst has a high mesoporosity (**Table 1**), tuned via the CVD technique. According to the authors, flowing FeCl₃ on a bed of N-C material (**Table 2**) led to the formation of high number of Fe-N₄ active sites, mostly located on the outer surface of the starting carbonaceous matrix, thus easily accessible to oxygen. The physico-chemical characterization highlighted the formation of a catalyst with an extremely high specific surface area and abundance of micro/mesopores, and abundance of Fe-N₄ moieties, compared to other Fe-based active sites [24]. It is known that larger pores favor the creation of a triple-phase boundary in PEFC electrodes, which are less affected by flooding during MEA operation [17,42]. The CVD synthesis route translated into the creation of a highly active catalyst, with a boosted activity toward the ORR. Interestingly, at the optimized temperature of 750 °C, the vapor of FeCl₃ reacts with Zn-N₄ from the ZIF starting precursor, leading to the formation of Fe-N₄ and release of ZnCl₂. Such a reaction occurs only on the surface of the carbon matrix, where ZnCl₂ can easily evaporate,

leading to the formation of Fe-N₄ active sites on the catalyst surface. The active sites located on the surface are more accessible, enabling the enhanced ORR activity [12]. This effect, together with the extraordinarily high specific surface area, gives rise to an extremely active catalyst. Similar effects of increased FeN₄ structures in the near edges of the carbon matrix have also been obtained by adding specific hydrogen donor/accepter functionalities near the active sites [12,56], yielding superior electroactivity performances and *TOF* values (1.1 e⁻ site⁻¹ s⁻¹, reached in the Electrocat Consortium [26]). A higher CVD temperature was not effective due to the decrease of the N content [57,58], with consequent reduction of the Fe-N₄ active sites. For this catalyst, Jiao et al. [24] estimated the different types of Fe moieties present in the catalyst via XPS and ⁵⁷Fe Mössbauer spectroscopy, and *in situ* XAS. Specifically, they calculated two utilization factors: U_{Fe} , defined as the ratio of the Fe atoms present as Fe-N₄ moieties with respect to the total Fe atoms in the catalyst, and U_{FeN_4} , defined as the ratio of the gas-phase accessible Fe-N₄ moieties with respect to all Fe-N₄ moieties present in the catalyst. Based on these definitions, the authors re-defined the *SD* based on the bulk Fe amount in the catalyst. They obtained $U_{Fe} = 0.9$ and $U_{FeN_4} = 1$, demonstrating that Fe~ST|b has a high density of Fe-N₄ sites, all of which are available for ORR. These values for U_{Fe} and U_{FeN_4} are much higher compared to those of similar Fe-N-C catalysts, at analogous total Fe amounts [40,59]. Notably, compared to Fe~ST|b, Fe~ST|a has much lower U_{FeN_4} , but higher Fe content (**Table 1** and radar plot **Figure 2**), suggesting that in this catalyst most of the Fe-N₄ sites are inaccessible to oxygen. This is also corroborated by the very different, and lower values of SD_{NO_2} compared to SD_{CO} [40]. In fact, CO as probe molecule penetrates better into pores, reaching a higher number of active sites, and giving rise to higher values of SD_{CO} .

Remarkably, Wan et al. [59] well-correlated the relationship among *SD*, *TOF*, porosity, and Fe content by synthesizing a series of very active catalysts (the best of which, TPI@Z8(SiO₂)-650-C reached a power density of 1.18 W cm⁻² in a 2.5 bar H₂/O₂ PEFC). The catalysts were synthesized by combining two different synthesis methods, soft templating by ZIF and hard templating by SiO₂, for a better tuning of the morphology, obtaining an extremely high specific surface area with enlarged mesopores (**Table 1**). By increasing the amount of Fe, these authors observed a huge increase of SD_{NO_2} , while the *TOF* values remained almost unchanged. On the other hand, U_{Fe} decreased with the increase of

Fe. They established a structure-property correlation for which the large external surface area and mesoporosity play crucial roles in maximizing SD , which is the predominant factor in determining a high current density at the PEFC level. In fact, the exposure of Fe-N₄ active sites to oxygen enhances mass transport properties in the catalytic layer of the MEA [46].

In **Figure 1**, catalysts Fe~RP|a, Fe~HT|a, Fe~HT|b, and Sn~RP are in the lower bottom/left quadrant, with low TOF and medium/low SD values. Interestingly, Fe~HT|a and Fe~HT|b exhibit the highest mass activity in this quadrant (**Table 1**). Both these catalysts are prepared by hard templating, that is by mixing silica powder with Fe nitrate and carbendazim, pyrolyzing at high temperature, and etching the silica [42]. The hard templating procedure produces a self-supported catalyst with an open-frame morphology [60], characterized by high specific surface area, many mesopores, and relatively low Fe content but high pyridinic-N (**Table 1** and radar plot in **Fig. 2**). Such a morphology displays a better activity compared to those of ZIF-derived catalysts mentioned above, but much lower compared to the catalysts prepared by CVD. The radar plot is very similar for these catalysts. Notably, Fe~HT|a has an intermediate value of U_{FeN_4} , of 0.43, with an enhancement of the intrinsic activity.

In the low SD / low TOF quadrant, we also found the Sn~RP catalyst, prepared by using Sn instead of Fe, with reactive polymerization of aniline (**Table 2**). This catalyst displays values in line with the other catalysts of the same quadrant, with relatively low values of all the physico-chemical characteristics, as evident from the radar plot (**Fig. 2**).

For a further enhancement of the mass activity, we have to move toward the top-left or bottom-right quadrants of the SD vs TOF map. In these quadrants, we find the catalysts Fe~RP|b and Fe~RP|c, both produced by reactive polymerization. No data are available for Fe~RP|c, but for Fe~RP|b the comparative radar plot highlights high values of Fe content, micro- and meso-porosity (**Table 1** and **Fig. 2**).

Sahraie et al. [52] prepared a series of mono- and bimetallic catalysts by reactive polymerization, mixing Fe and Mn: Fe~RP|d, Mn~RP, and bimetallic FeMn~RP. To better quantify the density and utilization of the active sites, they studied the effect of two or three heat treatments followed by acid leaching (**Table 2**). Interestingly, looking at the mono Fe-

N-C catalyst, the three steps of the heat treatment helped to slightly improve the SD values, at equal TOF . The heat treatment did not affect the nature of the active sites, which exchange the same number of electrons, but increased their availability to oxygen (**Fig. 1**: the black arrow indicated an increase in the SD of the Fe~RP|d from 2ht to 3ht). When Mn was added, with only two heat treatments, the SD was slightly reduced at equal TOF . However, a third heat treatment slightly changed the nature of the active sites, resulting in a higher TOF , but slightly lower SD , following the behavior of Mn~RP. More interestingly, the utilization factor U_{Fe} , increased with the number of heat treatments for both Fe~RP|d and FeMn~RP (**Table 1**). Notably, the heat treatment not only favored the formation of more active sites, but also increased the accessibility of the active sites to ORR. These results were supported by a slight increase of the surface-near elemental atomic Fe content when Mn was added, as measured by XPS (**Table 1**). Therefore, the mass activity was pushed in a favorable way toward the top/right quadrant of the SD vs TOF map.

Observing the two figures and the nature of active sites highlighted in the third column of **Table 2**, it is clear that the TOF depends on the physico-chemical properties of the support. It is difficult to determine possible correlations to elucidate which FeN_x active site has the greatest enhancement on the TOF value. For example, in the comparative work of Primbs et al. [40], the highest activity belongs to Fe~HT|b, Fe~HT|a, and Fe~ST|a, respectively, which contain a plurality of active sites as FeN_x and Fe nanoparticles (Fe(III)N₄ and Fe(II)N₄, α -Fe and γ -Fe). Interestingly, Fe~HT|b has the highest Fe utilization factor U_{Fe} , linked to the accessibility of the FeN_x sites. But the most stable catalyst under AST cycling is the less active Fe~RP|a, which contains a higher amount of only atomically dispersed Fe(III)N₄ and Fe(II)N₄ active sites, and the lowest U_{Fe} . In this work [40], Fe~ST|a was synthesized intentionally to contain a much higher content of Fe as compared to the “twin” catalysts synthesized by Zitolo et al. [58] with the same procedure but lower amounts of atomic Fe. Here, Fe_{0.5}-NC (containing only atomically dispersed FeN_x species) has almost the same activity of Fe_{1.0}-NC (containing atomically dispersed FeN_x, Fe nanoparticles and Fe carbide), but much higher stability under AST cycling. In agreement with the results of Primbs et al. [40]. Moreover, Zitolo et al. [58] demonstrated that the activity of Fe_{0.5}-NC can be enhanced

by pyrolysis with NH_3 . In fact, NH_3 increases the basicity of the carbon support, favoring the formation of $\text{FeN}_4\text{C}_{12}$ moieties [61,62].

Very recently, the porphyrin-like high-spin MN_4C_{12} moiety ($\text{M} = \text{Fe}$ [63,64] and Co [64]) has been identified as a highly active site towards ORR, leading to high values of *TOF*. Interestingly, the $\text{CoN}_4\text{C}_{12}$ moiety is slightly less active but more stable than the $\text{FeN}_4\text{C}_{12}$ moiety. On one hand, Li et al. [63] identified two active sites in their fresh $\text{Fe}_{0.5}\text{-NC}$ catalyst: a high-spin surface $\text{FeN}_4\text{C}_{12}$ and a low-spin $\text{FeN}_4\text{C}_{10}$ not accessible to oxygen (no Fe metal or other Fe species). Upon prolonged potential cycling in oxygen, they found a decreased amount of the $\text{FeN}_4\text{C}_{12}$ moiety, mostly by demetallation and localized carbon surface oxidation (in agreement with [33,45]), while the amount $\text{FeN}_4\text{C}_{10}$ remained constant. Indicating that the surface FeN_x active sites are non-durable, moving irreversibly from Fe(III) to Fe(II) as ferric oxide (in agreement with Zitolo et al. [58]). Conversely, the FeN_x active sites buried into the carbon matrix remained stable, and active towards ORR. Similarly, Xie et al. [64] compared the activity of Fe-N-C and Co-N-C catalysts, synthesized to have the same atomic percentage of metal and the same morphology (dominant microporous structure, only atomically dispersed MN_4C_{12} moieties, no nanoparticles and carbides present). At the fresh state, the two catalysts displayed similar activity, but Co-N-C was 4-folds more durable under potential cycling in oxygen. Oxygen promoted Fe demetallation from $\text{FeN}_4\text{C}_{12}$ moieties, since Fe catalyzes the Fenton reactions to a larger extent compared to Co. A detailed cross-linking of Mössbauer and XANES analyses coupled with DFT calculations confirmed that Co has a higher resistance to metal leaching compared to Fe. Predicted free energy barriers for demetallation showed higher values for Co compared to Fe. Thus, the stability of Co is correlated with the Co-N bond length, which is shorter compared to the Fe-N bond length. The shorter bond length of M-N, the higher the free energy [65].

Apparently, those catalysts containing a plurality of FeN_x sites and Fe particles buried in the carbon, thus not available for ORR at the fresh state, display lower activity at the beginning of life, but higher stability [33,45]. The exposure to ageing protocols leads to dramatic changes in the morphological structure of the catalyst, which in turn provokes changes more accentuated on *TOF* rather than *SD*.

Concluding on the observation of the map and radar plot, we can answer our question: high *TOF* values are more desirable, than high *SD* values. Accessibility of Fe-N₄ active sites plays a key-role on the catalyst activity. However, it is critical that less accessible active sites must simultaneously be present to enhance catalyst durability. Only a tailored and rational synthesis method can allow for an increase both of active and stable sites. The morphology of the catalyst, especially in terms of macropores, pyridinic-N, and porphyrin-like FeN₄C₁₂ sites, plays a crucial role in increasing the number of active sites placed not only on the outer surface of the carbon matrix, but also buried into it. On the contrary, too much bulk Fe is not effective. With the progresses made in the recent years, the Pt vs Fe gap on *TOF* values has been reduced from a factor x100 to x20 and further improvements are possible.

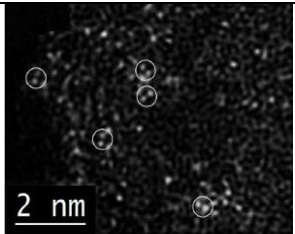
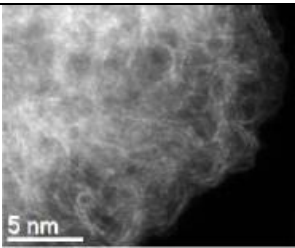
Table 1. Main physico-chemical data of the catalysts reported in **Fig. 2**. Mass activity measured by RDE or RRDE.

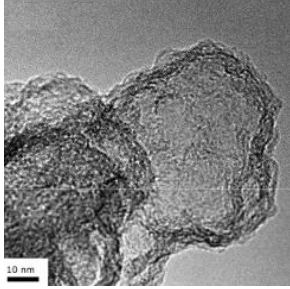
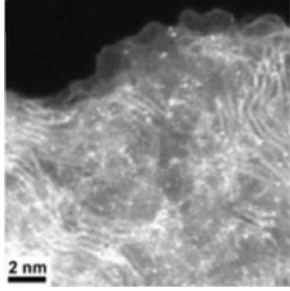
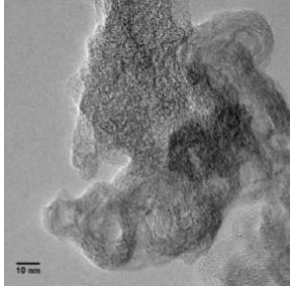
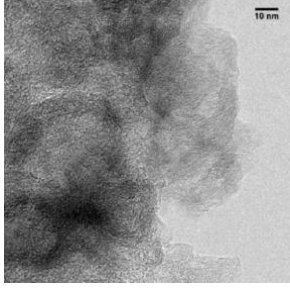
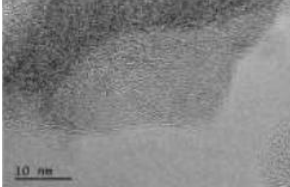
Catalyst [ref.]	S _{BET} [m ² g ⁻¹]	Micro- /mesopore volumes [cm ³ g ⁻¹]	Metal content [wt.% (ICP) / at.% (XPS)]	Pyridinic-N [at.% (XPS)]	Measured mass activity @ 0.8 V _{RHE} [A g ⁻¹]	TOF @ 0.8 V _{RHE} [e ⁻ site ⁻¹ s ⁻¹] TOF _{CO} / TOF _{NO2}	SD _{mass} [x10 ¹⁹ site g ⁻¹] SD _{CO} / SD _{NO2}	U _{Fe} factor [-]
Fe~ST a [40]	840	0.269 / 0.203	2.5 / 0.36	21.6	2.2	0.200 / 0.14	5.8 / 1.5	0.35
Fe~ST b [24]	1593	- / -	2.0 / -	-	15.6	0.780 / -	20 / -	0.90
Fe~ST c [48]	-	-	- / < 0.5	36.0	1.11	0.18 / -	3.84 / -	-
Fe~ST c(800) [48]	-	-	- / < 0.5	35.0	2.86	0.45 / -	3.99 / -	-
Co~ST [49,50]	-	- / -	1.00 / 0.40	23.8	0.2	0.029 / -	4.2 / -	-
Fe~RP a [40,41]	463	0.137 / 0.317	1.0 / 0.16	12.8	0.6	0.360 / 0.44	2.2 / 1.7	0.20
Fe~RP b [49]	665	0.200 / 0.450	3.92 / 0.70	14.0	2.4	0.156 / -	9.8 / -	-
Sn~RP [49]	364	0.110 / 0.210	3.78 / 0.30	9.7	0.9	0.155 / -	3.8 / -	-
Fe~RP c [51]	531	- / -	1.5 / -	-	-	1.550 / -	0.72 / -	-
Fe~RP d_2ht [52]	-	- / -	12 / -	-	-	1.4 / -	8.9 / -	0.082
Fe~RP d_3ht [52]	-	- / -	6.00 / 0.33	-	21	1.4 / -	9.1 / -	0.162
Mn~RP 2ht [52]	-	- / -	9 / 0.5	-	-	0.2 / -	4.0 / -	-
Mn~RP 3ht [52]	-	- / -	5 / 0.5	-	3.0	0.4 / -	4.3 / -	-
FeMn~RP 2ht [52]	-	- / -	5 (Fe) 3 (Mn) / -	-	-	1.4 / -	7.1 / -	0.124
FeMn~RP 3ht [52]	-	- / -	3 (Fe) 1 (Mn) / 0.58 (Fe)	-	17.6	1.6 / -	6.7 / -	0.231
Fe~HT a [40,42]	763	0.181 / 0.880	0.6 / 0.26	15.4	2.5	0.470 / 0.46	3.1 / 0.6	0.43
Fe~HT b [40,43]	593	0.103 / 0.920	0.8 / 0.25	11.6	3.1	0.710 / 0.8	2.0 / 0.2	0.78
Fe ₂ O ₃ /NC [44]	-	-	-	-	-	- / 1.2	- / 0.59	-
Fe _{0.5} /NC fresh [44]	-	-	- / 1.3	-	6.50	- / 7.1	- / 0.45	-
Fe _{0.5} /NC aged [44] -	-	-	- / 0.26* (see. Table 2)	-	2.94	- / 4.4	- / 0.62	-

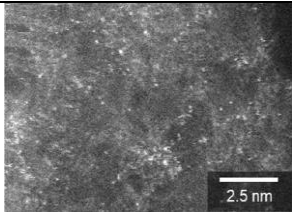
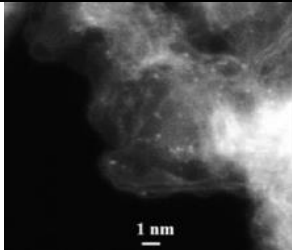
TPI@Z8(SiO ₂)-650-C family [59]	1648	40% / 60%	from 0.283 to 2.7 at.%			- / from 1.57 to 1.63	- / from 22.0 to 56.8 μ g ⁻¹	from 0.44 to 0.19
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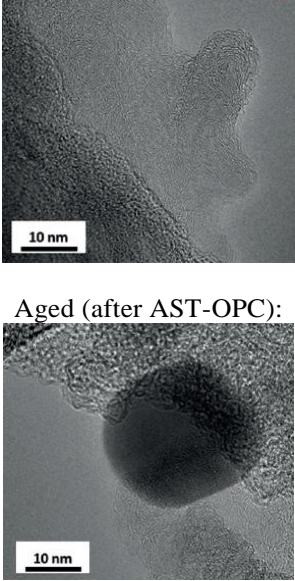
Table 2. Main physico-chemical characteristics of the catalysts reported in **Figure 1**.

Data taken from the literature (n.a.: not available).

Catalyst [ref.]	Schematic synthesis	Nature of the active sites and absolute wt% or relative % of each Fe species [from ^{57}Fe Mössbauer]	Morphology [from HAADF-STEM/TEM]
Fe~ST a [40]	Dry ball milling of ZIF-8 nanocrystals, Fe(II) acetate, and 1,10-phenanthroline. Ball-milling. Pyrolysis 1 h @ 1050 °C in Ar.	D1 high-spin Fe(III)N ₄ : 0.88 wt% D2 low-spin Fe(II)N ₄ : 0.62 wt% Magnetic α -Fe: 0.55 wt% Non-magnetic γ -Fe: 0.36 wt% Fe ₃ C: 0.09 wt%	
Fe~ST b [24]	Preparation of nanosized Zn(II) zeolitic imidazolate framework (ZIF-8). Mixing nanosized ZIF-8 and phenanthroline in ethanol and drying. Homogenization via low energy ball milling. Pyrolysis under Ar @ 1050 °C. The resulting N-C powder and FeCl ₃ as precursor placed in two separate ceramic boats, and pyrolyses 3 h @ 750 °C in Ar followed by cooling for the CVD of Fe on N-C.	D1 O ₂ -Fe(III)-N ₄ : 89% (air-accessible) relative area D3 high spin Fe(II)Cl ₂ : 11%	
Fe~ST c Fe~ST c_800 [48]	Fe(II) acetate, 1,10-phenanthroline, and ZIF-8, a Zn(II) zeolitic imidazolate framework mixed in a planetary ball miller with 4 cycles of 30 min each at 400 rpm. Flash pyrolysis under Ar flow at 1050°C for 1 h, followed by a fast cooling in cold Ar flow. For the Fe~ST c_800 sample: sequence of cleaning, CO uptake, and desorption cycles at the annealing temperature of 800°C.	Atomically dispersed FeN ₄ moieties as D1 low-spin Fe(II)N ₄ and D2 median-spin Fe(II)N ₄ . For the Fe~ST c_800 sample: increased content of graphitic N.	n.a.

Co~ST [49,50]	Zn(II) zeolitic imidazolate framework (ZIF-8), phenanthroline and Co(II) acetate ball-mixed with 4 cycles of 30 min each. The resulting powder pyrolyzed 1 h @ 1050 °C in Ar. Final activation in a flow of NH ₃ maintained for 2 h at 750 °C	From EXAFS measurement and DFT analysis: atomically dispersed cobalt ions and electronic state of three porphyrinic moieties: CoN ₄ C ₁₂ , CoN ₃ C _{10,porp} and CoN ₂ C ₅ .	
Fe~RP a [40,41]	Mixing of di-amino naphthalene C ₁₀ H ₁₀ H ₂ , APS (NH ₄) ₂ S ₂ O ₈ and FeCl ₂ in ethanol to form oligomers in a shape of self-assembled nanospheres. Drying. Heat treatment 2 h @ 1000 °C in N ₂ .	D1 high-spin Fe(III)N ₄ : 0.35 wt% D2 low-spin Fe(II)N ₄ : 0.65 wt%	
Fe~RP b [49]	FeCl ₃ dissolved in aniline and HCl. In situ polymerization with APS (NH ₄) ₂ S ₂ O ₈ . Addition of activated Ketjenblack. Resulting refluxed C/FeCl ₃ /PANI: ball-milled. Three steps of pyrolysis (1 st : 1 h @ 900 °C in N ₂ ; 2 nd and 3 rd : 3 h @ 900 °C in N ₂) with intermediate two acid leaching (1 M H ₂ SO ₄), washing and drying.	Atomically dispersed D1 and D2 doublets assigned to FeN ₄ moieties of different oxidation and spin states.	
Sn~RP [49]	Solution of aniline and HCl. In situ polymerization with APS (NH ₄) ₂ S ₂ O ₈ . Addition of activated Ketjenblack. Resulting refluxed C/PANI mixed with anhydrous SnCl ₂ and ball-milled. Three steps of pyrolysis (1 st and 2 nd : 1 h @ 900 °C in N ₂ ; 2 nd and 3 rd : 3 h @ 900 °C in N ₂) with intermediate two acid leaching / washing / drying steps (4 M HCl).	¹¹⁹ Sn Mössbauer (relative %): Sn(IV)-a: 30.6% Sn(II)-b: 47.7% Mixed ionic/covalent: 21.7%	
Fe~RP c [51]	Mixing of di-amino naphthalene C ₁₀ H ₁₀ H ₂ , APS (NH ₄) ₂ S ₂ O ₈ and FeCl ₂ in ethanol to form self-assembled oligomeric nanospheres.	n.a.	

	Solvent evaporation. 1 st heat treatment 2 h @ 950 °C in N ₂ . Acid leaching in 0.5 M H ₂ SO ₄ . Drying. 2 nd heat treatment 2 h @ 900 °C in N ₂ .		
Fe~RP d 3ht [52]	Monometallic catalysts: FeCl ₃ (or MnCl ₂) dissolved in aniline and HCl. In situ polymerization with APS (NH ₄) ₂ S ₂ O ₈ . Addition of Ketjenblack. Resulting C/FeCl ₃ /PANI heat	D1 low spin Fe(II)N ₄ : 1.33 wt% D2 intermediate spin Fe(II)Pc: 2.66 wt% D3 (NFe(III)N ₄)-O ₂ : 0.44 wt% D4 high spin XY-FeN ₄ (XY weak O and/or N ligands): 0.56 wt% Oxidized magnetic Fe particles: 1.02 wt%	n.a.
Mn~RP 3ht [52]	treated with 2 or 3 steps of pyrolysis (1 st : 1 h @ 900 °C in N ₂ ; 2 nd and 3 rd : 3 h @ 900 °C in N ₂) followed by 1 or 2 steps of intermediate acid leaching (2 h @ 900 °C in 2 M H ₂ SO ₄ , washing and drying). For the bimetallic catalyst: FeCl ₃ /MnCl ₂ molar ratio = 1/1.	n.a.	n.a.
FeMn~RP 3ht [52]		D1 low spin Fe(II)N ₄ : 1.17 wt% D2 intermediate spin Fe(II)Pc: 1.11 wt% D3 (NFe(III)N ₄)-O ₂ : 0.43 wt% Oxidized magnetic Fe particles: 0.29 wt%	n.a.
Fe~HT a [40,42]	Dispersion of silica in water, addition of carbendazim and ultrasonication, addition of iron nitrate Fe(NO ₃) ₃ and further ultrasonication. Drying. Grinding. 1 st pyrolysis 1.5 h @ in N ₂ . Adic leaching in 25 wt.% HF. Washing & drying. 2 nd pyrolysis 30 min h @ 950 °C in NH ₃ .	D1 high-spin Fe(III)N ₄ : 0.28 wt% D2 low-spin Fe(II)N ₄ : 0.39 wt% Non-magnetic γ-Fe: 0.13 wt%	
Fe~HT b [40,43]	Hard templating with fumed silica, commercially named as PMF-011904 (Pajarito Powder Inc.).	D1 high-spin Fe(III)N ₄ : 0.05 wt% D2 low-spin Fe(II)N ₄ : 0.19 wt% Magnetic α-Fe: 0.10 wt% Non-magnetic γ-Fe: 0.27 wt%	
Fe _{0.5} /NC [44]	Fe(II) acetate, 1,10-phenanthroline and ZIF-8 (0.5 wt % Fe in the precursor), mixed in a planetary ball-miller at 400 rpm for 2 h. Ramp pyrolysis in Ar up to 1050°C at 5°C min ⁻¹ , stay	Fresh Fe _{0.5} /NC: Atomically dispersed D1 and D2 doublets, confirmed by EXAFS with peaks of Fe-N and Fe-C backscatterings in FeN _x C _y moieties. Aged Fe _{0.5} /NC (after AST-OPC), by TEM, EDX and Raman	Fresh catalyst:

	<p>at 1050°C for 1 h, fast quenching under Ar.</p>	<p>analyses: FeN_xC_y moieties and many particles of 10-50 nm attributed to FeO and Fe_{0.90} (Wüstite). Local Fe content (Table 1): 0.26 at.% (EDX local analysis, cannot be considered as the average Fe content)</p>	 <p>Aged (after AST-OPC):</p>
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Conclusions and Outlook

We attempted to discuss in a concise form the characteristics of M-N-C electrocatalysts and bring the comparative study of their performance in RDE/RRDE to two main descriptors: (i) turn-over frequency (*TOF*) for ORR at a high potential of 0.8 V vs. RHE and (ii) site density (*SD*) expressed per unit mass of catalyst. This initial and simplified discussion leaves untouched the accessibility of the active sites as the next critical parameter. For most M-N-C catalysts only N₂ gas-accessible surface area (*S_{BET}*) is reported, while the electrochemically accessible surface area (*ECSA*) for PGM-free catalysts, including the M-N-C class, is not universally measured, and is rarely discussed. Water retention isotherms are not studied or published for these materials, and their hydrophobicity/hydrophilicity relationship to morphology is widely unexplored. All these materials and surface parameters will need to be combined into at least one morphology-dependent parameter (such as active site accessibility), expressed through roughness factor, Thiele modulus or effectiveness factor for the catalyst. This discussion naturally brings the structural parameters of the catalysts' particle to the level of aggregate, agglomerate and ultimately to catalyst layer (CL) design associated with the membrane electrode assembly (MEA) integration. The ultimate performance improvement and “moving the performance point” in **Fig. 1** simultaneously to

higher *TOF* and *SD* values (the desired outcome of the catalysts design) will depend on the successful implementation of new synthesis routes for designing catalysts with more accessible and stable active sites with high *SD* and *TOF*. The high *TOF* catalysts have specific synthesis barriers to overcome, especially considering the mass transport phenomena in the CL of MEAs, not discussed here. The observations provided here are leaving us with an optimistic picture that activity issues are clearly addressable within available technology and might already have been *de-facto* addressed in the laboratories of many groups pursuing M-N-C design.

What remains a great challenge, however, is the stability of catalysts during long-term operation. Along with specific atomistic factors of M-N-C active site deactivation (de-metalation), poisoning (usually reversible) and carbonaceous backbone material corrosion under fuel cell operating conditions (all the time above the thermodynamic stability potential of carbon oxidation), we would also bring attention to the possible role of morphological transformations during fuel cells' operation. Without forgetting the emerging need for such changes to be captured in *durability descriptors*, that should be integrated with the M-C-N *catalytic activity descriptors* discussed in this overview.

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit Author Statement

The authors contribute equally to the work by discussing and writing the manuscript, drawing the figures, along with approving its final version.

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