Electronic Supplementary Material (ESI) for Nanoscale Horizons.


# Supporting Information

## Ultrafine Pt Cluster and $RuO_2$ Heterojunction Anode Catalysts Designed for Ultra-low Pt-Loading Anion Exchange Membrane Fuel Cells

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Table S1. 5-year (2013-2019) average base metal price.

| Metal | Price ($/g) | Metal | Price ($/g) |
|---|---|---|---|
| Pt | 32.7 | Ni | 0.013 |
| Pd | 27.2 | Mo | 0.028 |
| Ru | 3.4 | W | 0.1 |
| Ir | 26.5 | Cu | 0.007 |

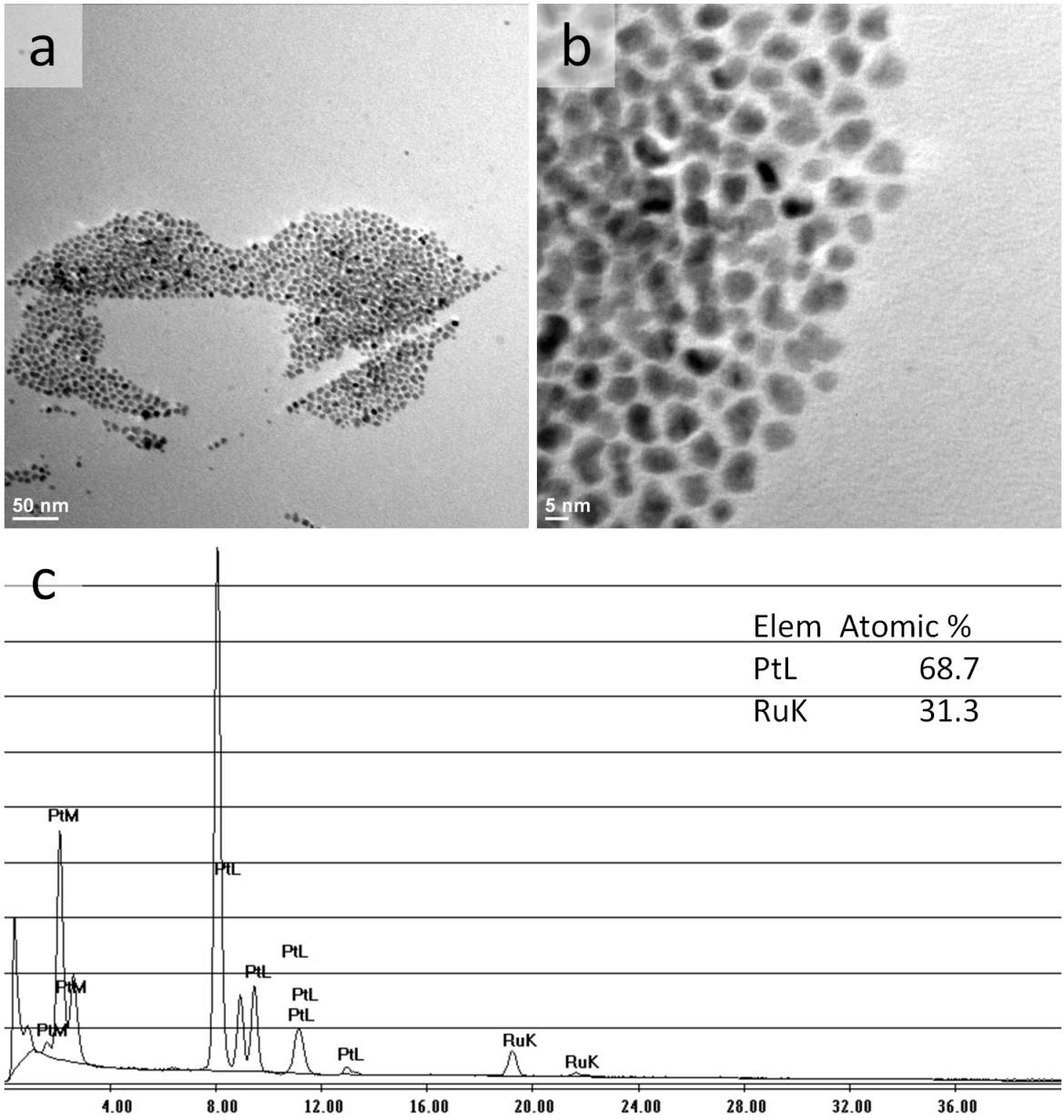



Figure S1. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in dibenzyl ether with oleylamine/oleic acid (0.5 mL each) as surfactants and 1,2-tetradecanediol (84 mg) as reducing agent.

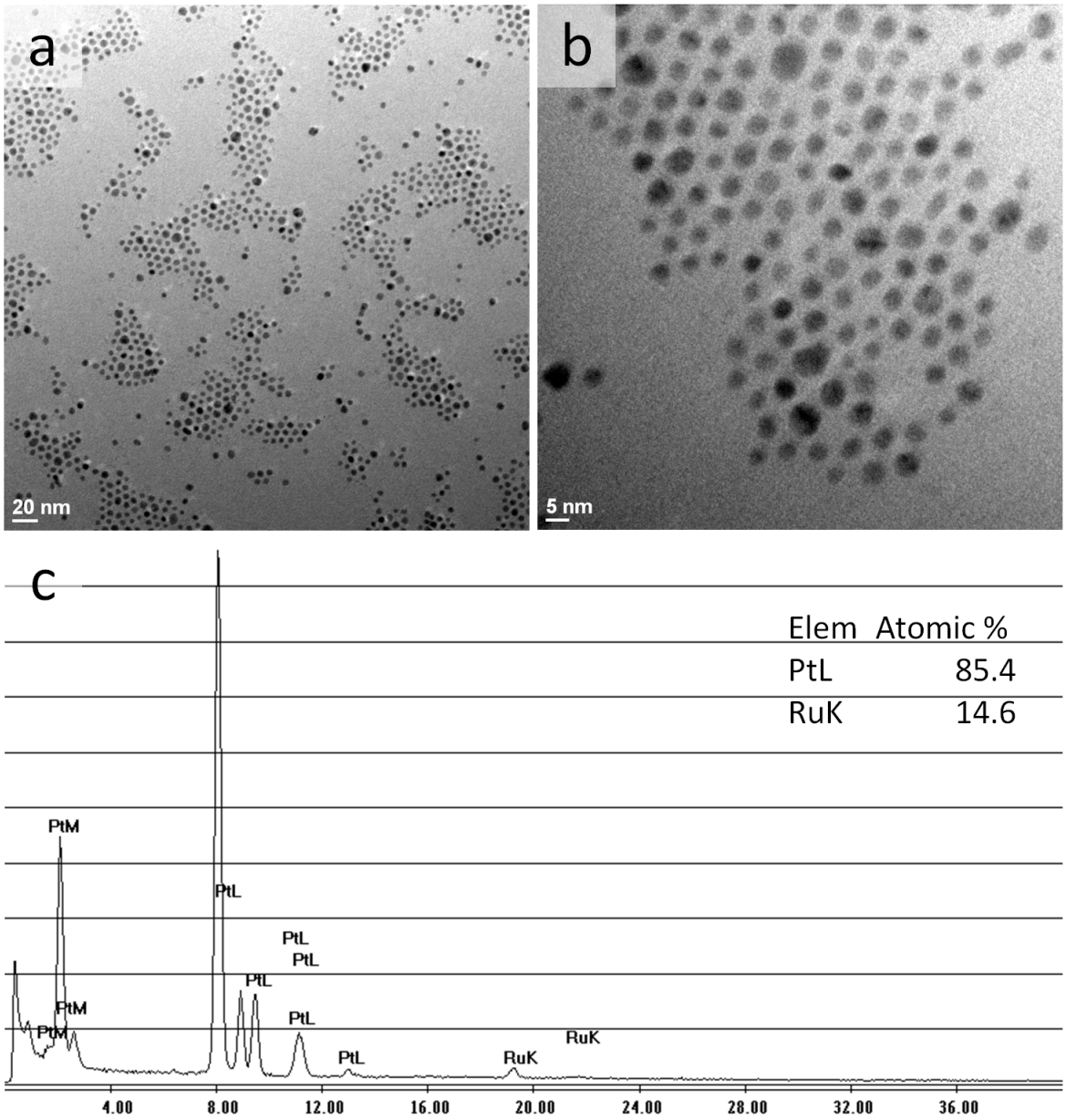



Figure S2. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in dibenzyl ether oleylamine/oleic acid (0.5 mL each) as surfactants and without 1,2-tetradecanediol.

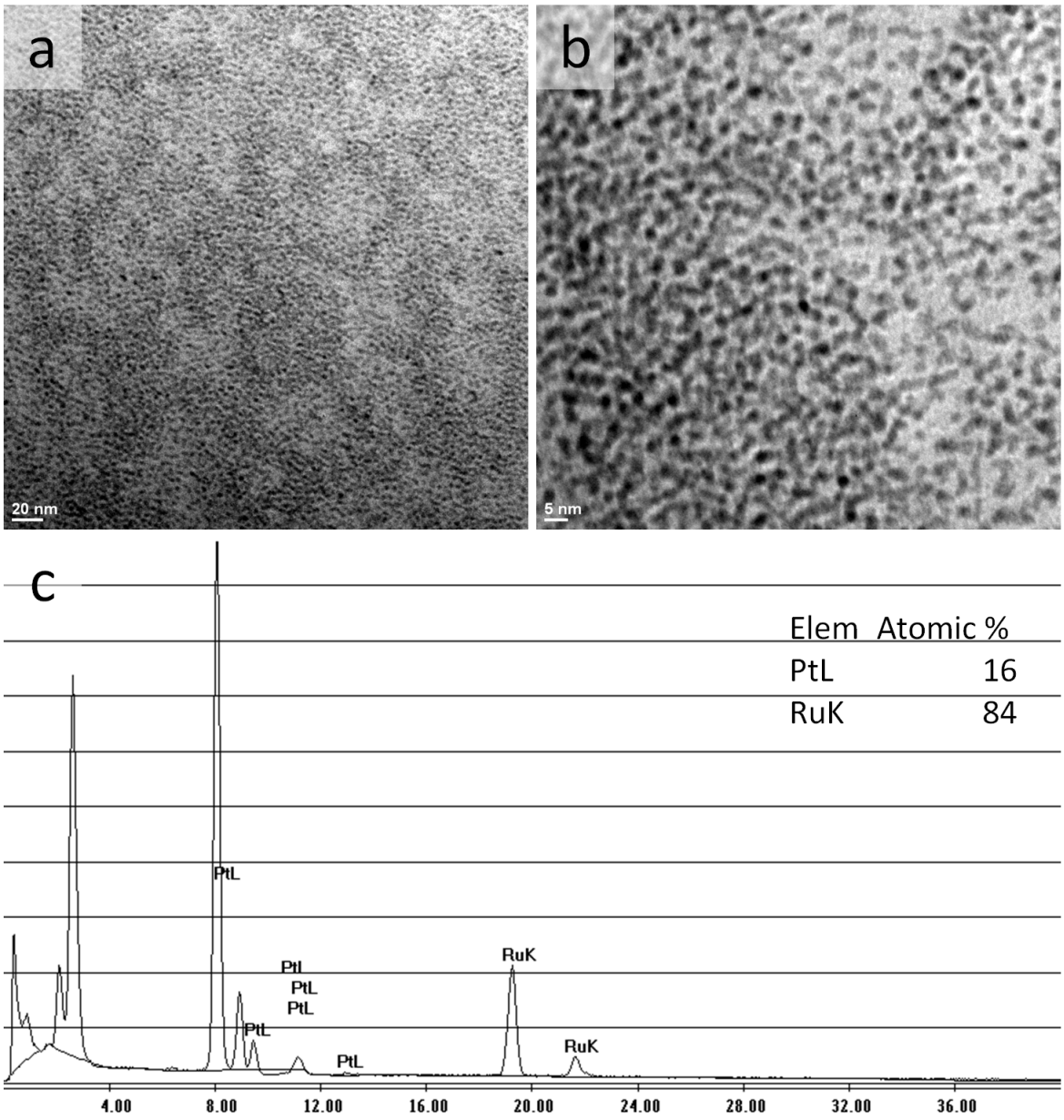



Figure S3. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in diphenyl ether with oleylamine (0.5 mL) as surfactant and 1,2-tetradecanediol (84 mg) as reducing agent.

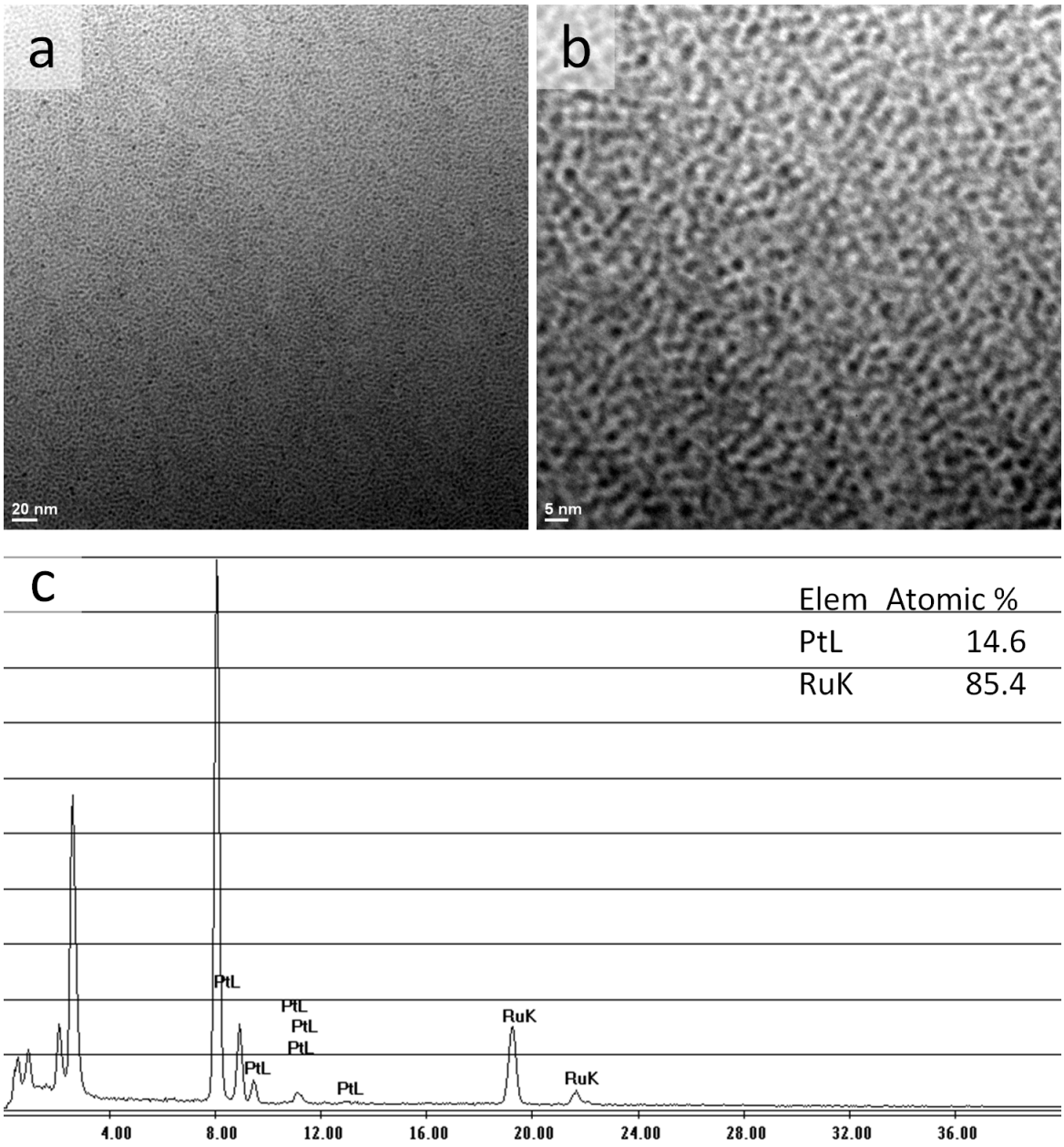



Figure S4. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in diphenyl ether with oleylamine (2 mL) as surfactant and 1,2-tetradecanediol (84 mg) as reducing agent.

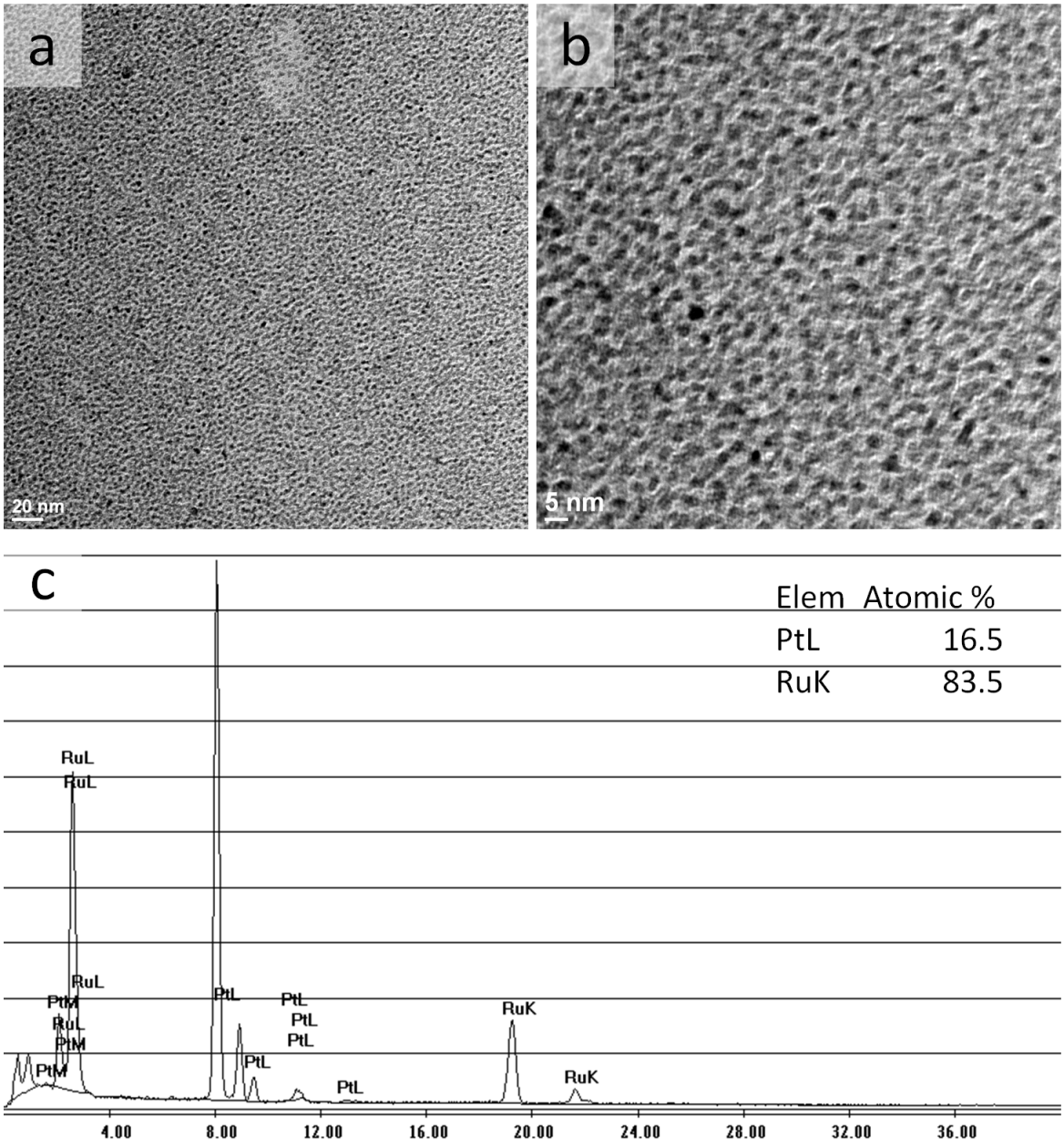



Figure S5. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in diphenyl ether with oleylamine (2 mL) as surfactant and 1,2-tetradecanediol (84 mg) as reducing agent (Confirmed reproducibility of Figure S4).

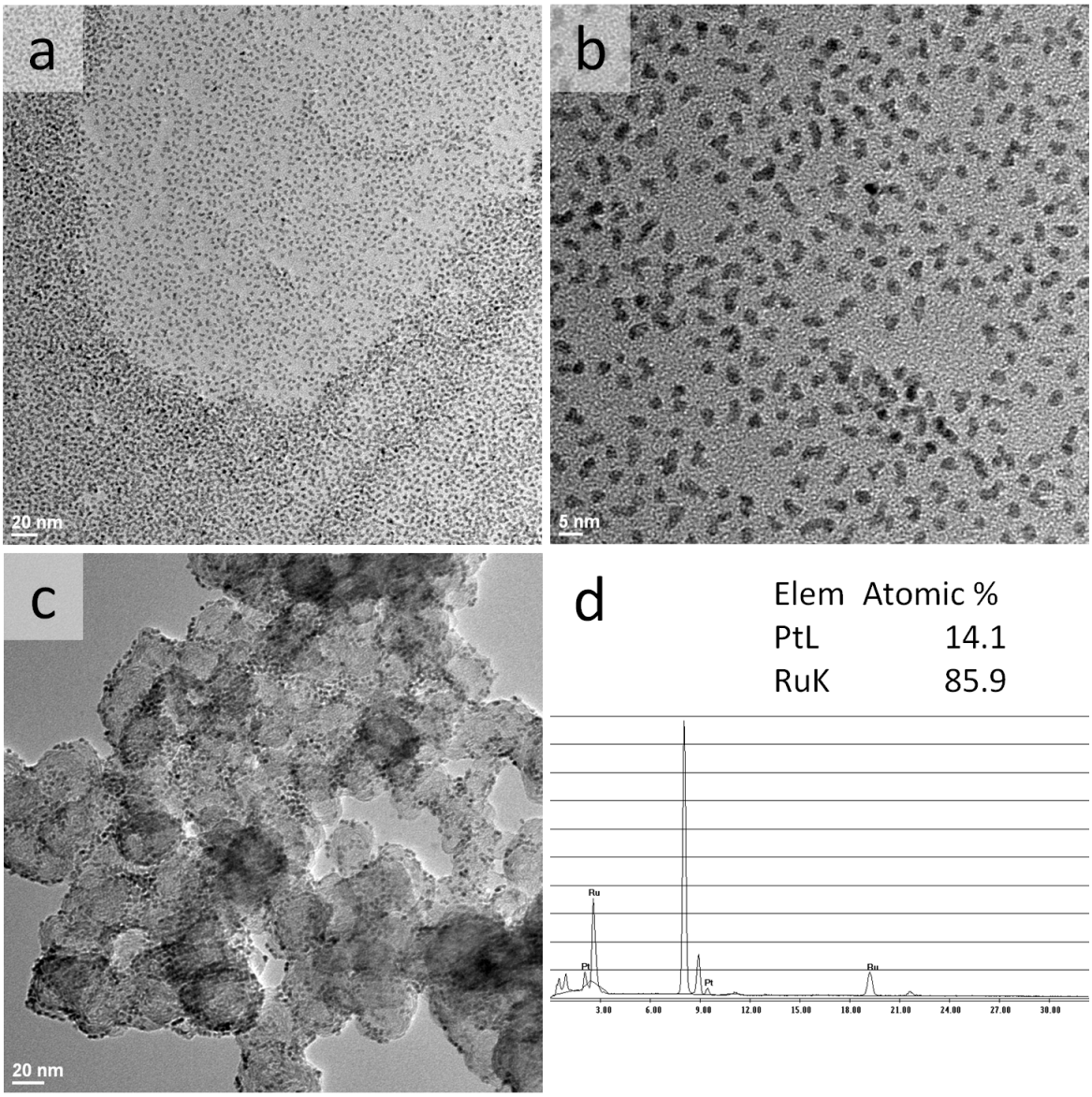



Figure S6. TEM images of 6 times scale-up PtRu nanoparticles (a, b) and after loading on carbon (c) with corresponding EDX spectroscopy (d).

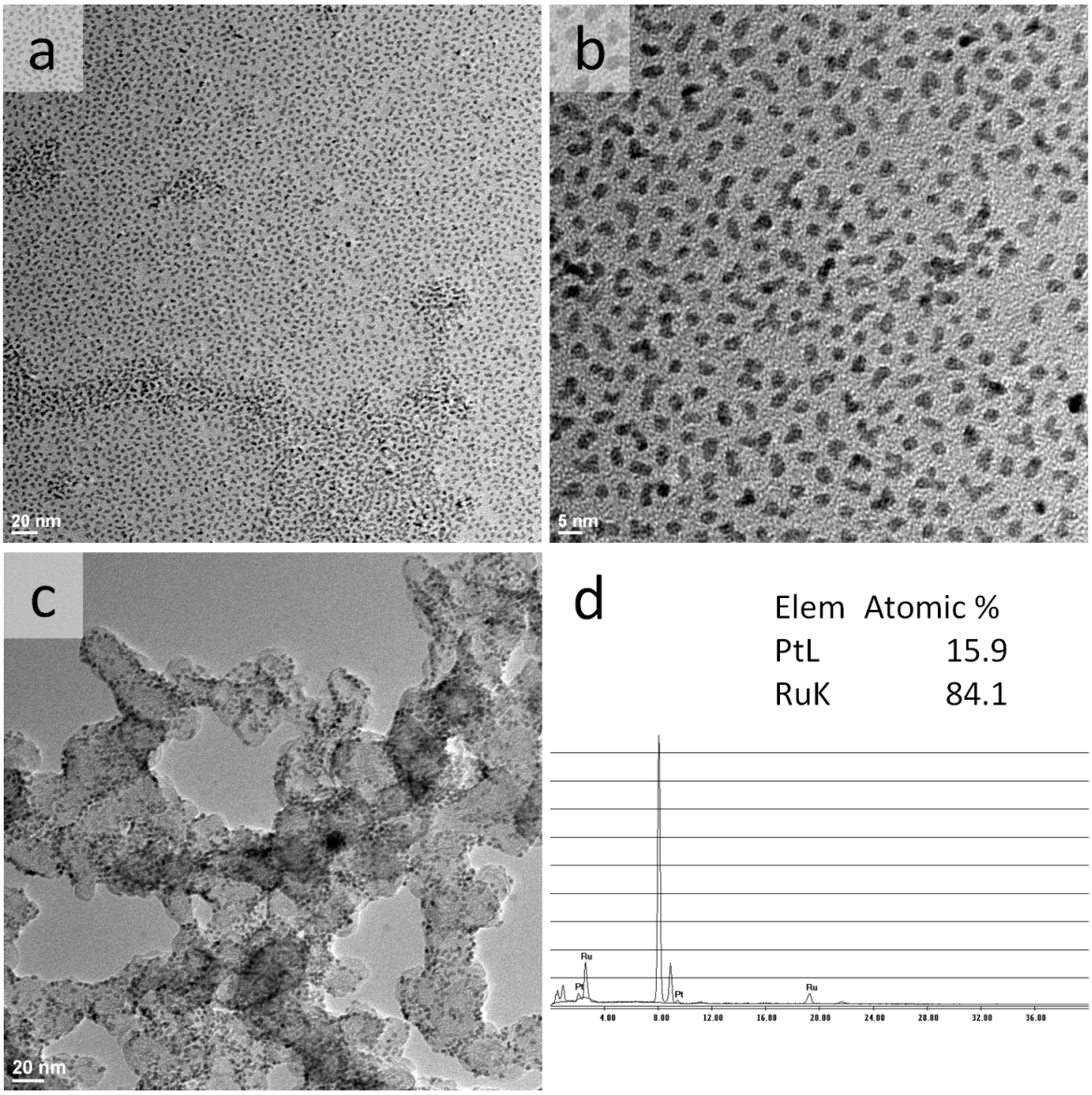



Figure S7. TEM images of 6 times scale-up PtRu nanoparticles (a, b), and after loading on carbon (c) with corresponding EDX spectroscopy (d). (reproducibility of Figure S8).

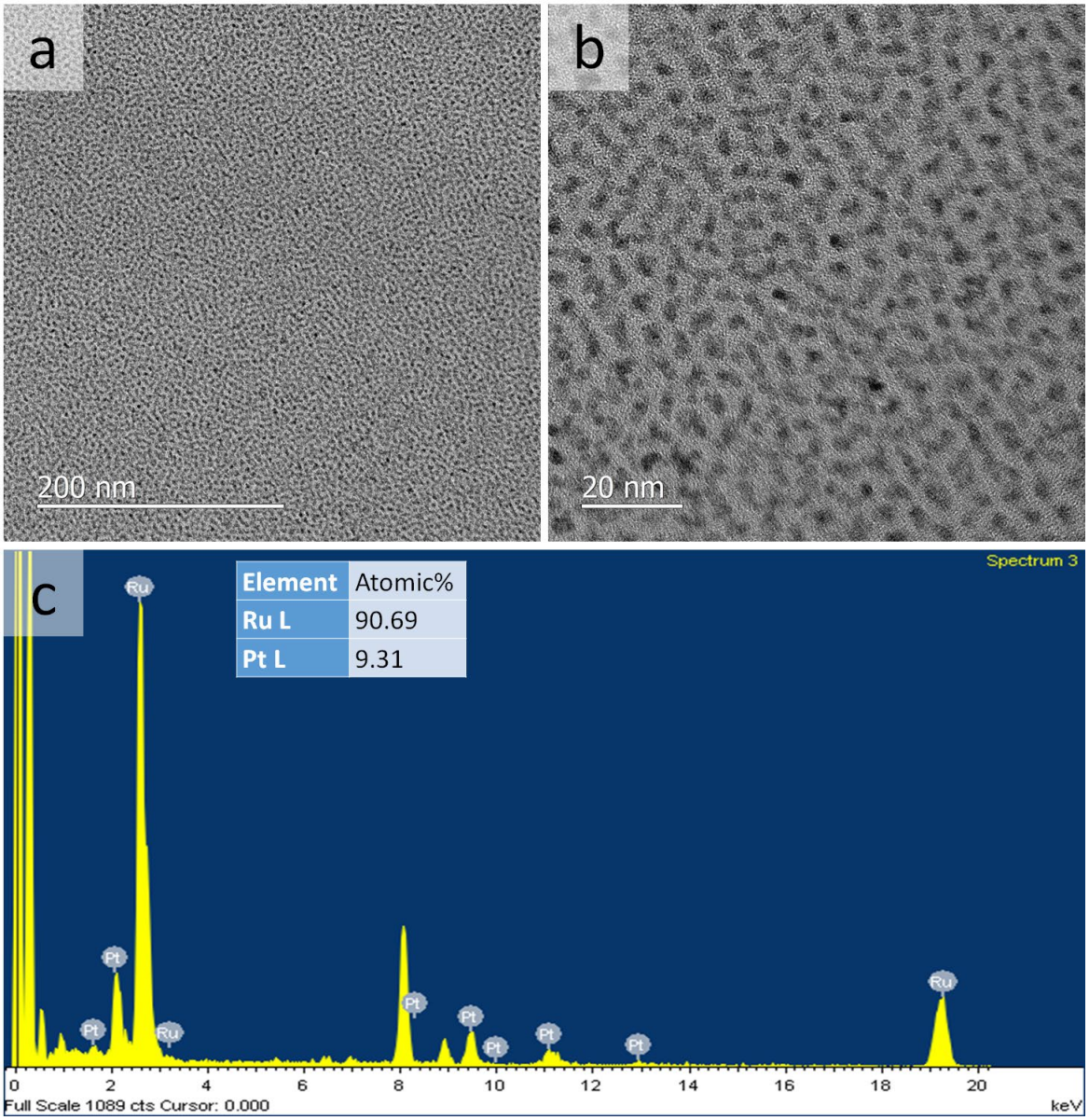



Figure S8. TEM images and EDX spectroscopy of PtRu nanoparticles synthesized in diphenyl ether with one-pot synthesis.

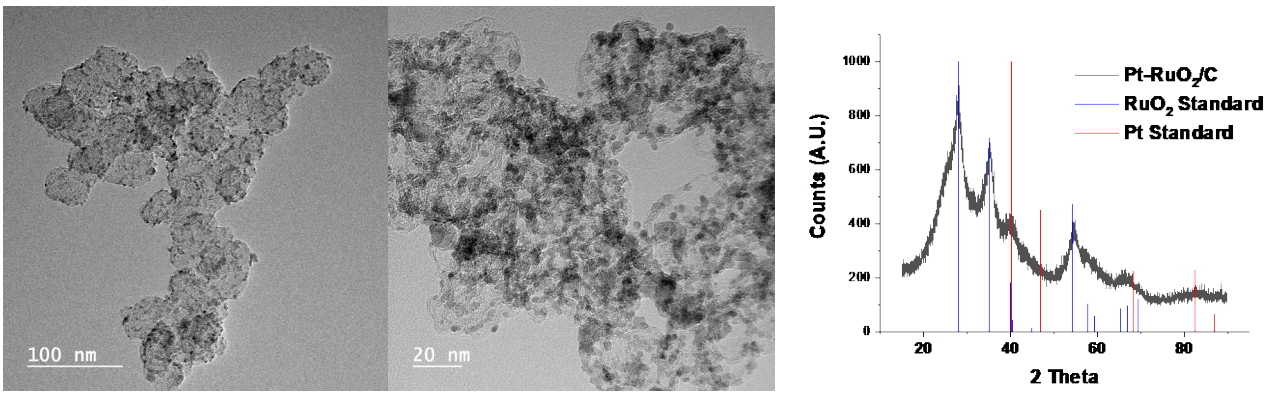



Figure S9. TEM images of scale-up Pt-$RuO_2$ nanoparticles supported on high surface area carbon and corresponding XRD pattern ($RuO_2$ standard PDF#01-071-4825, Pt standard PDF#01-087-0647).

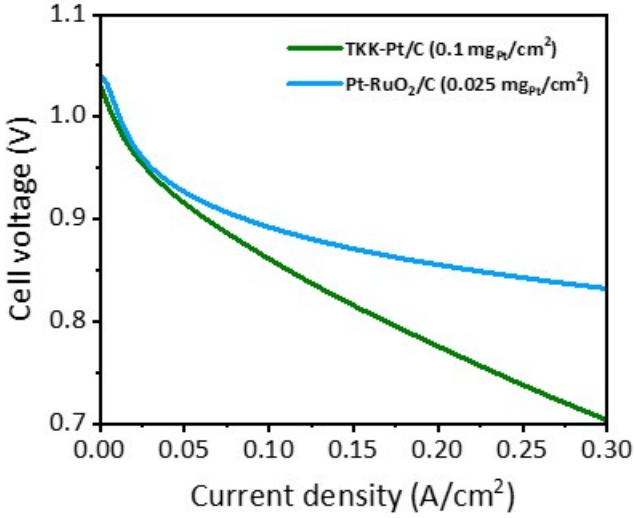



Figure S10. The kinetic performance of Pt/C and Pt-$RuO_2$/C anode catalyzed MEAs in terms of *iR* corrected polarization curves at 80 °C with humidified $H_2$ (2000 sccm) and $O_2$ (1000 sccm) at 285 kPa backpressure. Cathode: Pt/C (0.6 $mg_{Pt}/cm^2$).

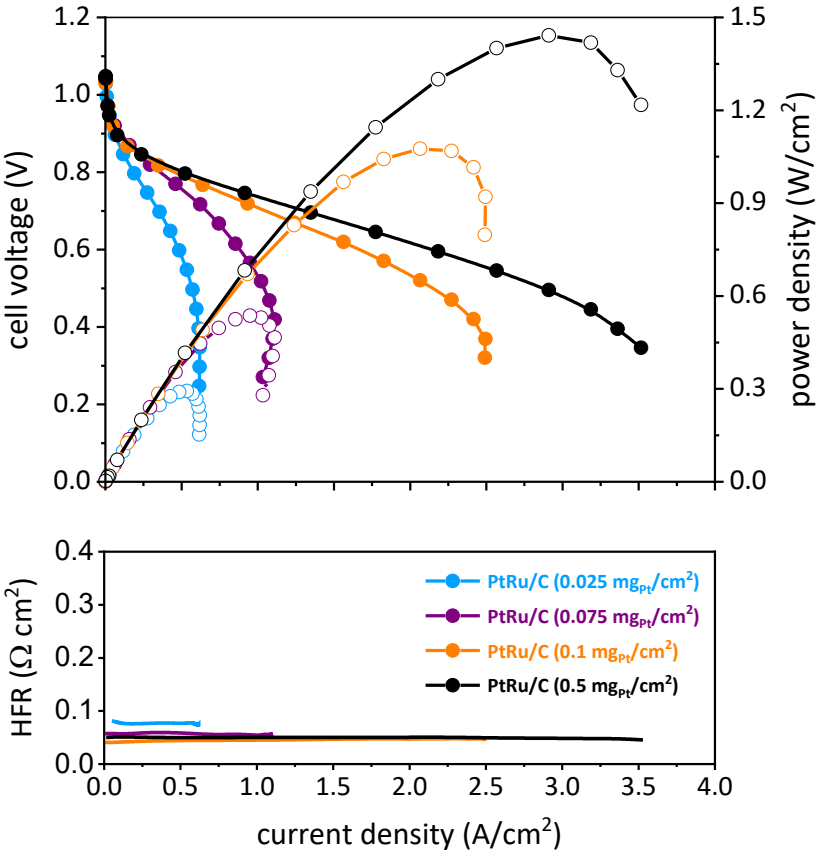



Figure S11. Effect of Pt loading at anode on AEMFC performance. Anode catalyst: JM HiSPEC 12100 PtRu/C, Cathode: JM HiSPEC 9100 Pt/C (0.6 $mg_{Pt}/cm^2$). Fuel cells performances were obtained at 80 °C with fully humidified 2000 sccm $H_2$ and 1000 sccm $O_2$ at 285 kPa backpressure.

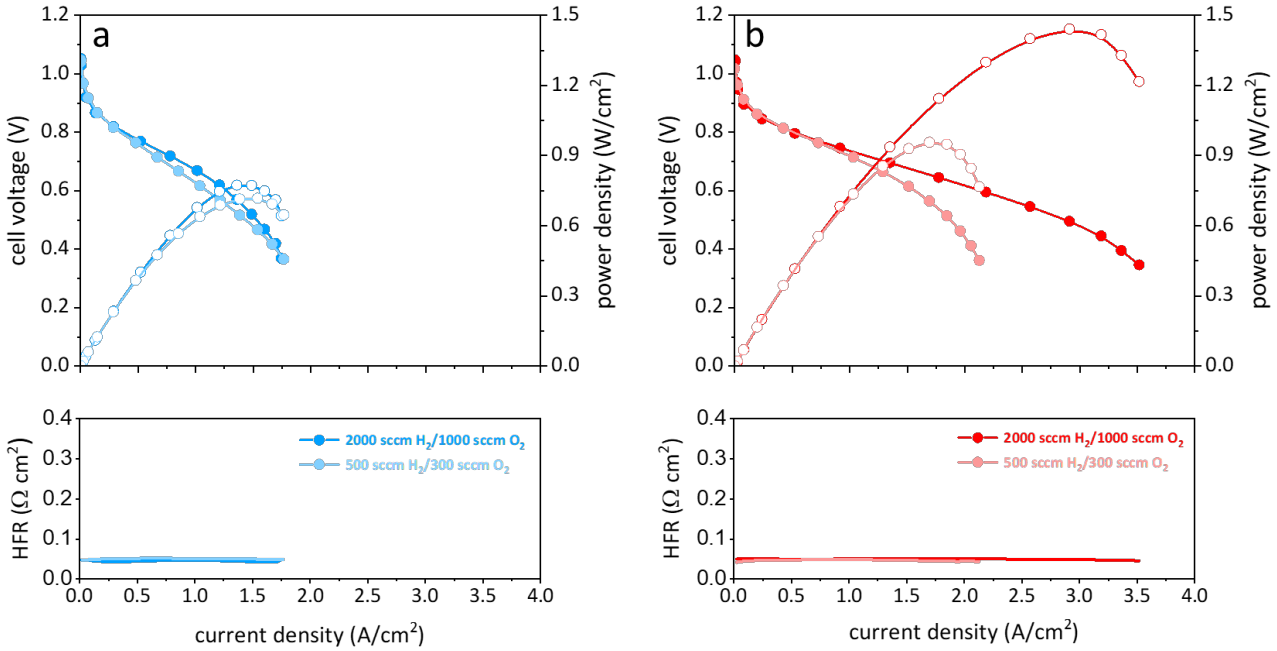



Figure S12. Effect of flow rate on AEMFC performance (a) Pt-$RuO_2$/C anode catalyzed MEA (b) JM HiSPEC 12100 Pt-Ru/C anode (0.5 $mg_{Pt}$ /$cm^2$) catalyzed MEA at 80 °C and 285 kPa backpressure under fully humidified gas feed.

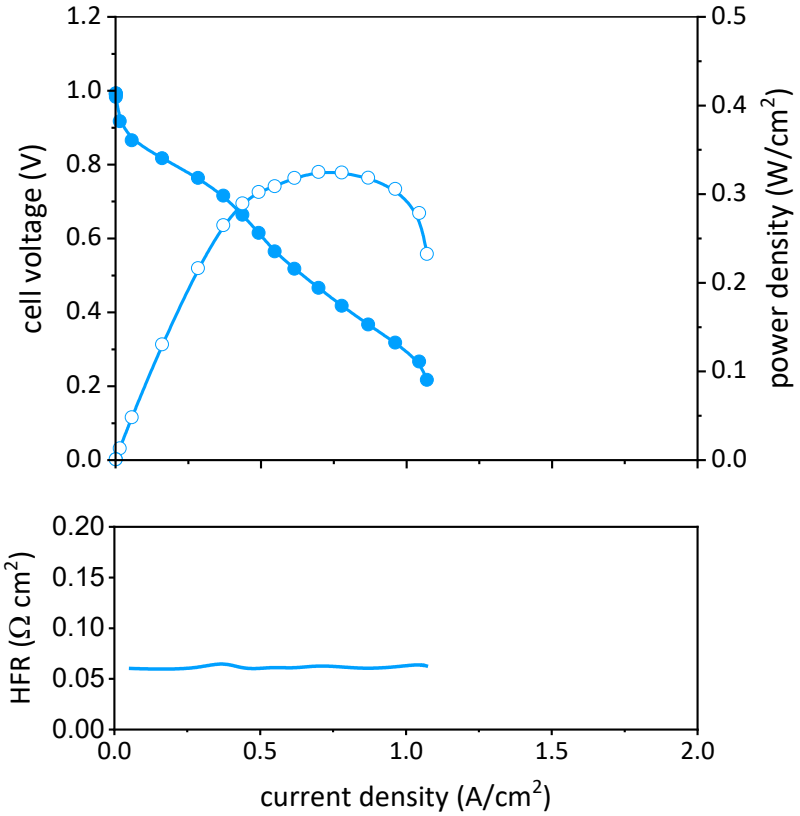



Figure S13. AEMFC performance in $H_2/CO_2$-free air with Pt-$RuO_2$/C as an anode and Pt/C as a cathode. Fuel cells performances were obtained with fully humidified 2000 sccm $H_2$ and 1000 sccm $CO_2$-free air at 285 kPa backpressure.

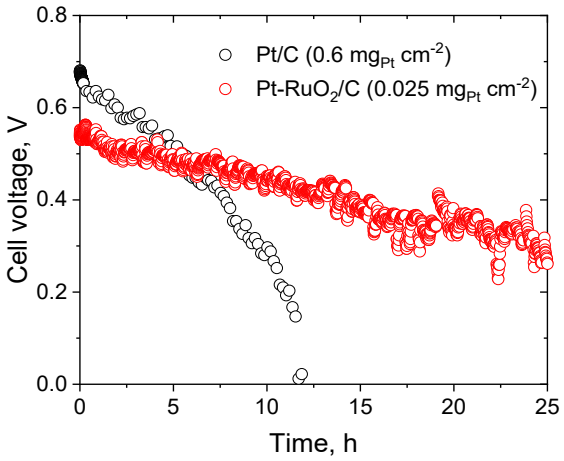
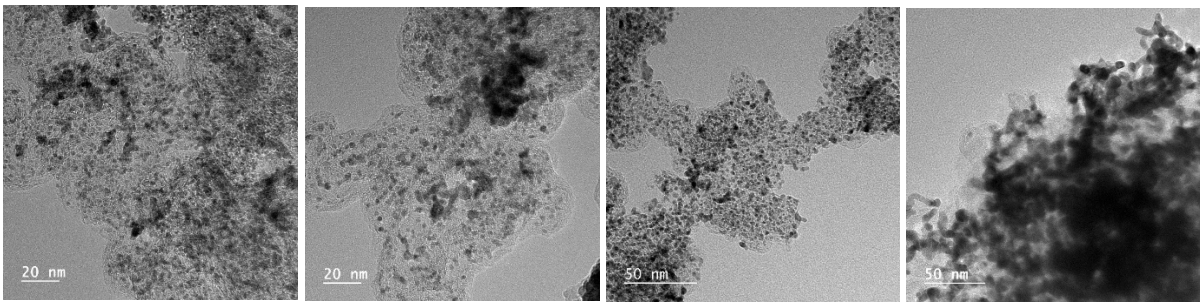



Figure S14. Cell voltage change during MEA life test at 80 °C, RH: 100%, flow rate: 1400 sccm $H_2$/300 sccm $O_2$, backpressure: 10 psig. MEA1: Pt/C anode (0.6 $mg_{Pt}$ $cm^{-2}$) and Pt/C cathode (0.6 mg Pt $cm^{-2}$). MEA2: Pt-$RuO_2$/C anode (0.6 $mg_{Pt}$ $cm^{-2}$) and Pt/C cathode (0.6 $mg_{Pt}$ $cm^{-2}$). Membrane: TPN (35 μm thick), Ionomer: FLN.




(a) (b) (c) (d)

Figure S15. Particle morphology change after 550-h hour MEA durability test at a constant voltage of 0.6 A $cm^{-2}$ at 80 °C; (a) Pt-Ru/C (anode) BOL (b) Pt-Ru/C (anode) EOL (c) Pt/C (cathode) BOL (d) Pt/C (cathode) EOL.

This figure is provided as an example of other MEA component degradation during the life test. The TEM images of PtRu/C anode catalyst and Pt/C after 550 h life test. The particle agglomeration is significant for Pt/C cathode, but we did not observe substantial particle size change for PtRu/C anode catalyst. These results suggest that anode catalyst degradation may be challenging to assess from MEA durability test.