Supplementary information

Aryl Ether-free Polymer Electrolytes for Electrochemical and Energy Devices

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Glossary of Acronyms

AEM: Anion exchange membrane
AEMFC: Anion exchange membrane fuel cell
AEMWE: Anion exchange membrane water electrolyzer
Alkyl-A: Alkyl ammonium
BTMA: Benzyltrimethyl ammonium
CE: Coulombic efficiency
CNT: Carbon nanotube
DABCO: Diazabicyclo[2.2.2] octane
DAPP: Diels–Alder polyphenylene
EE: Energy efficiency
ETFE: Ethylene tetrafluoroethylene
FE: Faradaic efficiency
FLN: Polyfluorene
HDPE: High density polyethylene
IEC: Ion exchange capacity
Im: Imidazolium
IPN: Interpenetrating polymer network
LDPE: Low-density polyethylene
MEA: Membrane electrode assembly
OCV: Open circuit voltage
QAPPT: Poly(*N*-methyl-piperidinium-*co*-*p*-terphenyl)
PAE: Poly(arylene ether)
PBI: Polybenzimidazole
PE: Polyethylene
PEEK: Poly(ether ether ketone)
PES: Poly(ether sulfone)
PGM: Platinum group metal
Pip: Piperidinium
PPD: Peak power density
PPO: Poly(*p*-phenylene oxide)
PTFE: Polytetrafluoroethylene
PSf: Polysulfone
Pyr: Pyridinium
ROMP: Ring opening metathesis polymerization
SEBS: Poly(styrene-*b*-(ethylene-*co*-butylene)-*b*-styrene)
VE: Voltage efficiency
WU: Water uptake

Table S1. H_2/O_2 AEMFC performance of MEAs using aryl ether polyaromatic membranes.

Year	Backbone	Cation group	X-linked or Composite	IEC (mequiv. g^{-1})	WU (%) (°C)	σ (mS cm^{-1}) (°C)	*t* (μm)	Ionomer	PPD (W cm^{-2})	Ref.
2015	PES	BTMA	n/a	1.0	68 (80)	110 (80)	50	PES	1.0	[1]
2018	PEEK	BTMA	Composite	1.8	95 (80)	119 (80)	15	PEEK	0.93	[2]
2019	PPO	Benzyl-Im	X-linked	1.7	105 (25)	62 (80)	50	PPO-BTMA	1.02	[3]
2019	PPO	Phenyl piperaziniu m	n/a	2.0	88 (60)	108 (60)	50	PPO-Phenyl piperazinium	1.21	[4]
2020	PES	BTMA	X-linked	1.1	53 (25)	30 (25)	50	PES	0.61	[5]
2021	PPO	BTMA	n/a	1.5	77 (80)	94 (80)	90	n/a	0.51	[6]
2021	PES	N-spirocy	n/a	1.4	25 (80)	136 (80)	46	PPO	0.85	[7]
2021	PES	N-spirocy	n/a	1.7	80 (25)	36 (80)[a]	55	ETFE-BTMA	1.48	[8]
2022	PPO[b]	BTMA	X-linked	2.2	130 (20)	160 (80)	20	PPO	0.58[c]	[9]
2022	PPO	BTMA	X-linked	3.6	147 (30)	52 (30)	50	Phenyl-Pip	0.58	[10]

[a] Cl^- form at 95% RH, [b] PPO/Olefinic IPN. [c] H_2/CO_2-free air.

Table S2. H_2/O_2 AEMFC performance of MEAs using aryl ether-free polyaromatic membranes.

AEM Synthesis	Year	Cation group	IEC (mequiv. g^{-1})	WU (%) (°C)	σ (mS cm^{-1}) (°C)	*t* (μm)	Ionomer	PPD (W cm^{-2})	Ref.
PBI	2016	Im	2.5	55 (25)	10 (25)	34	PBI	0.37	[11]
Metal-promoted	2017	BTMA	2.1	185 (30)	86 (80)	50	FLN	0.52	[12]
Diels–Alder	2018	Alkyl-A	2.0	83 (30)	48 (30)	30	Polyphenyl	0.88	[13]
Acid-catalyzed	2018	Alkyl-A	2.2	70 (80)	100 (80)	30	FLN	1.50	[14]
Acid-catalyzed	2018	Phenyl-Pip	2.7	58 (80)	137 (80)	30	Phenyl-Pip	1.50	[15]
Acid-catalyzed	2019	Phenyl-Pip	2.7	58 (80)	137 (80)	30	Phenyl-Pip	1.90	[16]
Acid-catalyzed	2019	Phenyl-Pip	2.4	90 (30)	193 (95)	25	Phenyl-Pip	1.89	[17, 18]
Acid-catalyzed	2019	Alkyl-A	1.2	42 (80)	95 (80)	36	Piperidine-co-terphenyl	1.20	[19]
Acid-catalyzed	2019	Alkyl-A	2.1	70 (80)	112 (80)	35	Polybiphenyl	1.60	[20]
Acid-catalyzed	2020	Alkyl-A	2.2	131 (80)	145 (80)	25	FLN	0.56	[21]
Acid-catalyzed	2020	Alkyl-A	2.3	76 (70)	125 (70)	50	Polycarbazole	1.61	[22]
Acid-catalyzed	2021	Phenyl & alkyl-Pip	1.9	80 (80)	105 (80)	45	PPO	1.18	[23]
PBI	2021	Alkyl-A	3.1	95 (80)	135 (80)	10	PBI	1.16	[24]
Acid-catalyzed	2021	Phenyl-Pip	2.8	180 (80)	138 (60)	22	FLN-Pip-co-Biphenyl-Pip	2.58	[25]
Metal-promoted	2021	Alkyl-Pip	1.5	75 (80)	95 (80)	n/a	PPO	0.56	[26]
Acid-catalyzed	2022	Alkyl-A	1.8	69 (30)	123 (80)	25	Polybiphenyl	0.60	[27]
Acid-catalyzed	2022	Alkyl-Pyr	1.9	27 (80)	120 (80)	21	FLN	0.50	[28]
Acid-catalyzed	2022	Alkyl-A	1.9	45 (30)	108 (80)	30	FLN	0.92	[29]
PBI	2022	Alkyl-Pip	2.0	83 (80)	80 (80)	20	PBI	0.79	[30]
Acid-catalyzed	2022	Phenyl-Pip	2.5	35 (80)	121 (80)	30	Phenyl-	1.20	[31]
PBI	2022	Im	2.9	73 (30)	n/a	5	PBI	1.40	[32]
Acid-catalyzed	2022	Phenyl-Pip	2.8	55 (20)	205 (90)	20	Phenyl-Pip	1.72	[33]
Acid-catalyzed	2022	Alkyl-A	1.8	69 (30)	155 (80)	20	Polycarbazole	1.85	[34]
Acid-catalyzed	2022	Phenyl-Pip	2.8	136 (80)	138 (60)	20	Phenyl-Pip	2.30	[35]
Acid-catalyzed	2023	Alkyl-A	2.1	112 (80)	152 (80)	n/a	Polycarbazole	0.55	[36]
Acid-catalyzed	2023	Alkyl-A & phenyl-Pip	3.0	72 (80)	157 (80)	25	Phenyl-Pip	0.65	[37]
Acid-catalyzed	2023	Phenyl-Pip	2.4	101 (30)	168 (80)	28	Phenyl-Pip	0.72	[38]
Acid-catalyzed	2023	Alkyl-A	1.7	96 (80)	126 (80)	35	Phenyl-Pip	0.74	[39]
Acid-catalyzed	2023	Phenyl-Pip	2.8	54 (80)	162 (80)	8	FLN-Pip-co-Biphenyl-Pip	0.78	[40]
Acid-catalyzed	2023	Alkyl-A	2.4	116 (80)	155 (80)	40	FLN	0.84	[41]
Acid-catalyzed	2023	Phenyl-Pip	2.5	10 (80)	143 (80)	20	Phenyl-Pip	0.85	[42]
Acid-catalyzed	2023	Alkyl-Pip	1.2	36 (80)	82 (80)	50	Alkyl-Pip	1.00	[43]
Acid-catalyzed	2023	Alkyl-A	2.1	45 (80)	180 (80)	30	FLN	1.00	[44]
Acid-catalyzed	2023	Alkyl-A	1.4	58 (80)	115 (80)	17	Phenyl-Pip	1.08	[45]
Metal-promoted	2023	Alkyl-A	2.5	71 (80)	136 (80)	24	Polyphenyl	1.27	[46]
Acid-catalyzed	2023	Alkyl-A	2.3	90 (80)	175 (80)	30	FLN	1.33	[47]
Diels–Alder	2023	Alkyl-A	2.0	48 (30)	83 (80)	25	Norbornene	1.40	[48]
Acid-catalyzed	2023	Phenyl-Pip	2.5	80 (80)	217 (80)	25	Phenyl-Pip	1.61	[49]
Acid-catalyzed	2023	Phenyl-Pip	2.7	97 (80)	148 (80)	20	FLN-Pip-co-Biphenyl-Pip	2.00	[50]
Acid-catalyzed	2023	Phenyl-Pip	3.1	230 (25)	143 (80)	20	FLN-Pip-co-Biphenyl-Pip	2.61	[51]
Acid-catalyzed	2024	Phenyl-Pip	2.8	150 (80)	126 (80)	20	FLN-Pip-co-Biphenyl-Pip	2.00	[52]

Table S3. H_2/O_2 AEMFC performance of MEAs using polyolefinic membranes.

AEM Synthesis	Year	Cation group	IEC (mequiv. g^{-1})	WU (%) (°C)	σ (mS cm^{-1}) (°C)	*t* (μm)	Ionomer	PPD (W cm^{-2})	Ref.
Radiation-graft	2016	BTMA	3.2	285 (25)	10 (25)	50	PVBC	0.61	[53]
Radiation-graft	2016	Benzyl-Pyr	2.1	n/a	n/a	52	Polysulfone	0.98	[54]
Vinyl	2017	Phenyl-A	1.4	42 (25)	35 (30)	22	SEBS	0.38	[55]
Radiation-graft	2017	BTMA	2.1	57 (30)	68 (80)[a]	25	ETFE-BTMA	1.16	[56]
Radiation-graft	2017	BTMA	2.9	105 (30)	76 (30)[a]	25	ETFE-BTMA	1.45	[57]
Anionic	2017	BTMA	1.4	52 (30)	112 (70)	50	PPO	0.30	[58]
Radiation-graft	2018	BTMA	2.5	149 (30)	208 (80)	22	ETFE-BTMA	2.0	[59]
Vinyl	2019	Alkyl-A	3.4	69 (25)	198 (80)	64	Norbornene	0.51	[60]
Anionic	2019	Alkyl-A	1.5	28 (25)	65 (80)	60	FLN	0.52	[61]
Radiation-graft	2019	BTMA	2.4	121 (25)	155 (25)[a]	21	ETFE-BTMA	2.6	[62]
Vinyl	2019	Alkyl-A	3.8	73 (25)	152 (80)	10	ETFE-BTMA	3.5	[63]
Anionic	2020	BTMA	1.4	45 (30)	40 (60)	n/a	SEBS	0.59	[64]
Vinyl	2020	Alkyl-A	3.5	73 (25)	147 (80)	10	Norbornene	3.2	[65]
Vinyl	2021	Alkyl-Pyr	1.9	588 (30)	100 (80)	21	PPO	1.1	[66]
Vinyl	2021	BTMA	1.5	98 (80)	116 (20)	50	PPO	0.64[b]	[67]
Vinyl	2022	Benzyl-Pip	1.6	9 (80)	102 (80)	4	Phenyl-Pip	1.00	[68]
Vinyl	2022	Benzyl-Pip	1.9	141 (25)	172 (80)	35	PPO	0.98	[69]
ROMP	2023	Alkyl-cyclic A	1.7	87 (80)	67 (80)	n/a	Phenyl-Pip	1.0	[70]
Vinyl	2023	Alkyl-A	2.0	71 (25)	109 (80)	30	FLN	1.07	[71]
Vinyl	2023	Alkyl-Pyr	2.5	75 (95)	130 (90)	40	Styrene	0.66	[72]

[a] Cl^- form. [b] H_2/CO_2-free air and PGM-free cathode.

Table S4. H_2/CO_2-free air AEMFC performance of aryl ether-free MEAs.

Year	AEM backbone	Cation group	IEC (mequiv. g^{-1})	*t* (μm)	Cathode catalyst	Operating temp. (°C)	Ionomer	PPD (W cm^{-2})	Ref.
2017	ETFE	BTMA	2.1	21	Ag/C	70	ETFE-BTMA	0.65	[73]
2018	LDPE	BTMA	2.5	22	Ag/C	80	ETFE-BTMA	0.66	[59]
2019	LDPE	BTMA	2.9	25	N-C-CoO_x	65	ETFE-BTMA	0.66	[74]
2019	Phenyl-Pip	Phenyl-Pip	2.4	25	Ag	95	Phenyl-Pip	0.92	[16]
2021	ETFE	BTMA	2.1	50	Co–Fe/CNT	60	Polystyrene	0.8	[75]
2021	HDPE	BTMA	2.4	20	Fe-N-C	80	ETFE-BTMA	1.0	[76]
2022	Phenyl-Pip	Phenyl-Pip	2.4	18	Ni-H_2-NH_3 (anode)	95	Phenyl-Pip	0.5	[77]
2022	Phenyl-Pip	Phenyl-Pip	2.4	15	Zn-N-C	80	Phenyl-Pip	0.83	[78]
2022	Phenyl-Pip	Phenyl-Pip	n/a	20	Co-Mn-oxide	80	Phenyl-Pip	0.83	[79]
2023	Phenyl-Pip	BTMA	n/a	22	Fe-N-C	85	Phenyl-Pip	0.51	[80]
2023	Phenyl-Pip	Phenyl-Pip	2.7	25	Ni (anode)	80	Phenyl-Pip	0.55	[81]
2023	Phenyl-Pip	Phenyl-Pip	2.4	15	Metal-free carbon	80	Phenyl-Pip	0.60	[82]

Table S5. AEMFC durability of MEAs using aryl ether polyaromatic membranes.

Year	Back bone	Cation group	IEC (mequiv. g^{-1})	*t* (μm)	Ionomer	PPD (W cm^{-2})	AEMFC durability				Ref.
							Temp (°C)	*i* (A cm^{-2})	Time (h)	Loss (%)	
2012	PAE	BTMA	2.7	50	PAE-BTMA	0.19	60	0.3 V	55	> 70	[83]
2019	PPO	Benzyl-Im	1.7	50	PPO	1.02	70	0.6	58	29	[3]
2020	PPO	Im	1.4	25	PPO	0.75	60	0.2	960	70	[84]
2021	PPO	BTMA	1.5	90	n/a	0.51	60	0.2	24	39	[6]
2021	PPO	Alkyl-phenyl Pip	2.0	15	PPO	1.5	70	0.6	120	14	[85]
2021	PES	N-spirocy	1.3	10	ETFE-BTMA	1.1	61	0.6	550[a]	7	[8]
2022	PPO	BTMA	2.3	n/a	PPO	0.45	60	0.3	120	13	[86]
2023	PES	Pyr	1.8	n/a	PES	0.49	60	0.1	10	14	[87]

[a]H_2/CO_2-free air. [b]PGM-free cathode. [c]Cl^- form at 95% RH, [d]PPO/olefinic IPN.

Table S6. AEMFC durability of MEAs using aryl ether-free membranes.

Year	Backbone	Cation group	IEC (mequiv. g^{-1})	*t* (μm)	Ionomer	PPD (W cm^{-2})	AEMFC durability				Ref.
							Temp (°C)	*i* (A cm^{-2})	Time (h)	Loss (%)	
2012	DAPP	BTMA	1.7	50	Phenyl-BTMA	0.20	60	0.3 V	300	67	[83]
2018	Phenyl	Phenyl-Pip	2.7	30	Phenyl-Pip	1.50	80	0.2	120	10	[15]
2018	Phenyl	Alkyl-A	2.2	30	FLN	1.50	80	0.6	550	15	[14]
2019	Phenyl	Phenyl-Pip	2.4	25	Phenyl-Pip	1.89	95	0.5[a]	300	14	[17]
2019	Norbornene	Alkyl-A	3.3	10	ETFE-BTMA	3.5	80	0.6	500[a]	10	[88]
2020	FLN	Im	2.2	25	FLN	0.62	60	0.2	115	21	[89]
2020	DAPP	Alkyl-A	2.6	39	FLN	1.22	80	0.6	900	24	[90]
2021	Phenyl	Phenyl-Pip	2.8	22	FLN-co-Bipheny	2.58	80	0.4	100	27	[25]
2021	HDPE	BTMA	2.4	20	ETFE-BTMA	~2.0	80	0.6[c]	150	10	[76]
2021	FLN-co-phenyl	Alkyl-A	2.8	15	FLN	2.34	70	0.2	200	4	[91]
2021	Phenyl	Phenyl-Pip	2.8	20	Phenyl-Pip	2.80	60	0.2	500	29[b]	[35]
2021	ETFE	Phenyl-Im	1.7	25	ETFE-BTMA	0.71	60	0.05	670	35	[92]
2022	DAPP	Alkyl-A	2.0	30	FLN	1.50	80	1.0	200	10	[93]
2022	Carbazole	Alkyl-A	2.3	50	Carbazole	1.05	60	0.6	1,000	15	[94]
2020, 2022	Norbornene	Alkyl-A	3.3	10	Norbornene	3.2	75	0.6	2,000, 3,600	4, 19	[95, 96]
2022	PE	Ferrocenium	1.7	60	PE-ferrocenium	0.74	120	0.5	500	3.9	[97]
2023	DAPP	Alkyl-A	2.0	25	Norbornene	1.41	80	1.0	200	15	[48]
2023	Phenyl	Phenyl-Pip	2.4	15	Phenyl-Pip	0.91	80	0.25[c]	100	25	[82]
2023	Phenyl	Phenyl-Pip	2.5	25	Phenyl-Pip	1.61	60	OCV	1,000	8	[49]
2023	Ethylene-styrene	Phenyl-Pip	2.5	40	Phenyl-Pip	0.66	80	OCV	600	9	[72]

[a]H_2/CO_2-free air, [b]recoverable loss, [c]PGM-free cathode

Table S7. AEMWE performance of MEAs (pure water-fed).

Year	Backbone	Cation group	IEC (mequiv. g^{-1})	*t* (μm)	Ionomer	Temp (°C)	Catalyst		*i* at 1.8 V	Ref.
							anode	cathode		
2019	Polystyrene	Benzyl-Pip	1.2	n/a	SEBS-Pip	50	IrO_2	Pt/C	0.08	[98]
2020	FAA-3-PK-1		1.3	75	n/a	50	NiFe	NiMo	0.45	[99]
2020	Phenyl-Pip		3.3	20	Phenyl-Pip	80	FeNi	Pt/C	0.8	[100]
2020	Phenyl	Alkyl-A	2.6	26	BTMA	85	NiFe	NiMo	0.9	[101]
2020	Phenyl	Alkyl-A	2.6	26	BTMA	85	NiFe	PtRu	2.75	[101]
2021	Phenyl-Pip		2.2	40	Phenyl-Pip	69	IrO_2	Pt/C	0.75	[102]
2021	Phenyl	Alkyl-A	2.0	50	FLN	60	IrO_2	Pt/C	1.0	[103]
2021	FLN-*co*-Phenyl-Pip		2.8	30	FLN-*co*-Phenyl-Pip	80	IrO_2	Pt/C	0.7	[104]
2021	SEBS	Alkyl-A	1.7	32	FLN	60	IrO_2	Pt/C	0.82	[105]
2021	Phenyl	Alkyl-A	2.0	50	FLN	60	IrO_2	Pt/C	0.75	[105]
2022	SEBS	Alkyl-Pip	1.1	n/a	SEBS-Alkyl-Pip	60	IrO_2	Pt/C	0.75	[106]
2022	Norbor	Alky-A		30	Norb-Alkyl-A	60	IrOx	Pt/C	0.4	[107]
2022	Phenyl-Pip		2.7	30	Phenyl-Pip	60	FeNi	Pt/C	1.2	[108]
2022	Phenyl-Pip		3.0	50	Phenyl-Pip	80	$NiFe_2O_4$	NiFeCo	2.0 at 1.76V	[109]
2023	Phenyl-Pip		1.8	60	Phenyl-Pip	80	IrO_2	PtRu/C	0.6	[110]
2023	Biphenyl	Alkyl-A	2.6	50	Phenyl-alkyl-A	60	IrO_2	Pt/C	0.7	[111]
2023	Phenyl-Pip		2.5	25	Phenyl-Pip	90	FeNi	Pt/C	1.27	[49]
2023	X37-50	Im	1.1	50	FAA-3	70	NiFe	$NiMoO_4$	0.6	[112]

Table S8. AEMWE performance of MEAs (KOH-fed).

Year	Backbone	Cation group	IEC (meq uiv. g^{-1})	*t* (μm)	Ionomer	KOH (M) / Temp (°C)	Catalyst		*i* at 1.8 V	Ref.
							anode	cathode		
2018	Polystyrene	Im	1.1	50	Benzyl-Im	1/60	NiFe	NiFeCo	0.5	[113]
2019	FAA-3-50		1.3	50	FAA-3	1/50	IrO_2	Pt/C	0.46	[113]
2019	Polystyrene	Pyrroli	2.7	60	n/a	1/60	NiFe	NiMo	0.25	[114]
2019	PBI-Im		2.5	50	n/a	1/60	NiAlMo	NiAlMo	0.85	[115]
2020	FAA-3-PK-1		1.3	75	n/a	0.1/50	NiFe	NiMo	1.0	[99]
2020	Carbazole	Alkyl-A	2.3	50	Carbazole	1/70	IrO_2	Pt/C	2.5	[22]
2020	BenzIm		2.3	50	FAA-3	1/60	Ir black	Pt/C	1.84	[116]
2020	Polystyrene	Im	1.1	50	Nafion	1/80	Fe-NiMo	NiMo	0.73 at 1.55 V	[117]
2020	Polystyrene	Im	1.1	50	n/a	1/45	IrO_2	CuCO	1.26	[118]
2020	Phenyl	Alkyl-A	2.6	26	BTMA	1/85	NiFe	PtRu	5.3	[101]
2021	Fumapem-3-PE-30		1.9	30	FAA-3	1/50	IrO_2	NiCu	0.9	[119]
2021	Polystyrene	Pyrroli	2.0	80	PTFE	1/80	NiFe	NiMo	0.4	[120]
2021	X37-50	Im	1.1	50	n/a	1/50	NiFeCo	NiFeCo	0.8	[121]
2021	X37-50	Im	1.1	50	Nafion	1/60	NiCo	Pt/C	1.0	[122]
2021	Phenyl	Alkyl-A	2.0	50	FLN	0.1/60	IrO_2	Pt/C	2.0	[103]
2021	Polysulfone	BTMA	1.0	48	n/a	1/80	Ni	Pt/C	1.0	[123]
2021	FLN-*co*-Phenyl-Pip		2.7	30	FLN-*co*-Phenyl-Pip	1/80	IrO_2	Pt/C	3.5	[104]
2022	Phenyl-Pip		2.3	30	Phenyl-Pip	1/85	IrO_2	Pt/C	0.7	[124]
2022	FLN	Alkyl-A	2.0	43	FLN	1/70	IrO_2	Pt/C	0.9	[125]
2022	FAA-3-50		1.3	50	FAA-3	1/50	NiFe	Pt/C	1.1	[126]
2022	FAA-3-50		1.3	50	FAA-3	1/70	Ni-IrO_2	Pt/C	1.2	[127]
2022	Polystyrene	Im	1.1	50	FAA-3	1/60	Perov	Pt/C	1.16	[128]
2022	BenzIm		2.5	50	BenzIm	1/60	Ir	Pt/C	1	[129]
2022	SEBS	Alkyl-Pip	1.9	n/a	FAA-3	1/70	IrO_2	Pt/C	1.0	[130]
2022	Phenyl-Pip		3.0	50	Phenyl-Pip	1/80	$NiFe_2O_4$	NiFeCo	0.12	[109]
2022	FAA-3-50		1.3	50	FAA-3	1/60	NiFe-PS	NiFe-PS	1.5	[131]
2022	Norbornene	Alkyl-A	n/a	30	Alkyl-A	0.3/50	PbRuO	PtNi	1.65	[132]
2022	Phenyl	Alkyl-A	n/a	n/a	Phenyl-Alkyl-A	1/55	NiFe	Pt/C	1.0	[133]
2022	Carbazole	Alkyl-A	2.3	50	PTFE	1/80	CuCO	Pt/C	3.0	[134]
2023	Phenyl	Pip	1.8	60	Phenyl-Pip	1/80	IrO_2	PtRu/C	2.0	[110]
2023	Phenyl	Pip	2.9	15	Phenyl-Pip	1/80	IrO_2	Pt/C	1.4	[135]
2023	Biphenyl	Alkyl-A	2.6	50	Phenyl-alkyl-A	1/60	IrO_2	Pt/C	1.24	[111]
2023	Polysulfone	Alkyl-A	1.3	45	Polysulfone-Alkyl-A	1/80	Ni	Pt/C	0.85	[136]
2023	X37-50	Im	1.1	50	n/a	1/80	FeNiOOH	NC@Ru-CoP	1.56	[137]
2023	Phenyl-Pip		2.5	25	Phenyl-Pip	1/90	FeNi	Pt/C	5.5	[49]
2023	Phenyl-Pip		2.4	80	Phenyl-Pip	1/80	CO_3O_4	Pt/C	1.9	[138]
2023	FLN-*co*-Phenyl-Pip		3.0	50	Phenyl-Pip	1/80	Fe-Ni-Co	PtRu/C	7.8	[139]

Table S9. AEMWE durability of MEAs.

Year	Backbone	Cation group	IEC (meq uiv. g^{-1})	*t* (μm)	Ionomer	AEMWE durability					Ref.
						Mode	Temp (°C)	Initial V	Time (h)	Loss (%)	
2014	Phenyl	BTMA	1.7	80	Phenyl-BTMA	0.2 A cm^{-2}/ water	50	2.2	2,200	400 mV	[140]
2014	A201		1.8	28	PTFE	0.5 cm^{-2}/ 1 wt.% K_2CO_3	43	1.9	1,000	150 mV	[141]
2016	PolybenzIm		2.5	34	FAA-3	0.025 A cm^{-2}/ 1 M KOH	60	2.2	244	300 mV	[11]
2018	Polystyrene-Im		1.1	50	Im	1 A cm^{-2}/ 1 M KOH	60	1.9	2,000	5 mV h^{-1}	[113]
2019	PolybenzIm		2.5	50	n/a	1 A cm^{-2}/ 1 M KOH	60	2.08	150	0.3 mV h^{-1}	[142]
2020	Phenyl		2.6	26	Styrene-BTMA	0.2 A cm^{-2}/ water	60	1.8	160	1.3 mV h^{-1}	[101]
2021	X37-50		1.1	50	Im	0.5 A cm^{-2}/ water	60	1.9	170	120 mV	[143]
2021	Phenyl-Pip		2.2	40	Phenyl-Pip	0.5 A cm^{-2}/ water	55	1.86	180	0.67 mV h^{-1}	[102]
2021	Phenyl-Alkyl-A		2.2	30	FLN	0.75 A cm^{-2}/ 1wt% K_2CO_3/ 60-100 psig	50	1.92	400	0.3 mV h^{-1} (recoverable); 0 (non-recoverable)	[105]
2021	FLN-*co*-Phenyl-Pip		2.7	30	FLN-*co*-Phenyl-Pip	0.5 A cm^{-2}/ 1 M KOH	60	1.6 V	1,000	0	[104]
2021	Polystyrene		0.9	50	Styrene-Im	1 A cm^{-2}/ 1 M KOH	60	1.85	12,000	0.02 mV h^{-1}	[144]
2022	Phenyl-Pip		2.3	30	Phenyl-Pip	0.2 A cm^{-2}/ 1 M KOH	60	1.75	400	0.11 mVh^{-1}	[124]
2022	SEBS	Alkyl-Pip	1.1	n/a	SEBS-Alkyl-Pip	2 V/ 0.1 M KOH	60	0.7 A cm^{-2}	300	1.0 mVh^{-1}	[106]
2022	Norbornene		3.4	30	Norbornene	1 A cm^{-2}/pure water	60	2	500	93.5 mV h^{-1}	[107]
2022	Norbornene		3.4	30	Norbornene	1 A cm^{-2}/0.1 M NaOH	60	1.8	600	stable	[145]
2022	Phenyl-Pip		2.7	30	Phenyl-Pip	0.5 A cm^{-2}/ pure water	60	1.7	180	100 mV	[108]
2022	Phenyl-Pip		3.0	50	Phenyl-Pip	0.2 A cm^{-2}/ pure water	80	1.6	200	stable[a]	[109]
2022	PolybenzIm		2.1	50	BenzIm	1 A cm^{-2}/ 1 M KOH	60	1.78	100	stable	[129]
2022	Phenyl-Alkyl-A		n/a	n/a	Phenyl-Alkyl-A	1 A cm^{-2}/ 1 M NaOH	55	1.72	400	93 mV h^{-1}	[133]
2022	FAA-3-50		1.3	50	FAA-3	1 A cm^{-2}/ 1 M NaOH	60	1.73	300	80 mV h^{-1}	[131]
2022	FAA-3-50		1.3	50	FAA-3	1 A cm^{-2}/ 1 M KOH	50	2	2,000	reversible loss	[126]
2022	Carbazole	Alkyl-A	2.3	50	PTFE	0.5 A cm^{-2}/ 0.1 M KOH	45	1.73	3,000	11.3 mV h^{-1}	[134]
2023	Phenyl-Pip		1.8	60	Phenyl-Pip	1 A cm^{-2}/ 0.1 M KOH	60	1.92	300	170 mV	[110]
2023	X37-50		1.1	50	Im	0.5 A cm^{-2}/ 1 M KOH	80	1.65	100	Stable	[137]
2023	Phenyl-Pip		2.5	25	Phenyl-Pip	0.5 A cm^{-2}/ 1 M KOH	60	1.62	2,500	0.015 mV h^{-1}	[49]
2023	X37-50	Im	1.1	50	Im	1.8 V cm^{-2}/ pure water	70	0.63 A cm^{-2}	192	2.9%	[112]
2023	Polysulfone	BTMA	2.2	44	Polysulfone	0.5 A cm^{-2}/ 2 M NaOH	30	1.75	480	3%	[146]
2023	Phenyl	Alkyl-A	2.6	50	Phenyl-Alkyl-A	1 A cm^{-2}/ 1 M KOH	60	1.85	3,500	6.5 mV h^{-1}	[111]
2023	Aemion+ (Composite)		~2.5	85	Nafion	1 A cm^{-2}/ 1 M KOH	70	2.0	5,000	0.6 mV h^{-1}	[147]
2023	Phenyl-Pip		2.4	80	Phenyl-Pip	2 A cm^{-2}/ 0.1 M KOH	80	2.1	600	5 □V h^{-1}	[138]

2023	FLN-*co*-Phenyl-Pip	3.0	50	Phenyl-Pip	1.5 A cm^{-2}/ 1 M NaOH	60	1.8	2,000	50 □V h^{-1}	[139]

[a]using phosphate buffer.

Table S10. Flow battery performances of membranes. Data was extracted from graphs by DigitizeIt Version 2.3.3. IEC values of Nafion are taken from the specification sheets.

Type	Year	Membrane	CE (%)	VE (%)	EE (%)	IEC (mequiv. g^{-1})	Ref.
AEM	2018	PAEK-API 2.0	97.5	83.1	81.1	1.43	[148]
	2018	QPPP-1	100.0	70.0	70.0	1.6	[149]
	2018	QPPP-2	99.0	87.0	86.1	2.0	[149]
	2018	QPPP-3	99.0	81.0	80.2	2.4	[149]
	2018	IMPPP-1	100.0	67.0	67.0	1.2	[149]
	2019	PE/PP-g-PVBTMA 33%	90.1	81.1	73.0	1.48	[150]
	2019	PE/PP-g-PVBTMA 210%	91.5	82.7	75.7	3.52	[150]
	2019	QA-OMPAEK20	97.9	83.7	81.9	2.33	[151]
	2019	QA-TMPAEK40	95.5	84.7	81.0	2.46	[151]
	2019	BM-TMIm 4 NN	99.7	81.8	81.5	2.75	[152]
	2019	BM-TMIm 4 NF	99.2	84.7	84.0	2.55	[152]
	2019	BM-TMIm 4 FN	99.2	86.7	86.0	2.58	[152]
	2019	BM-TMIm 4 FF	97.6	86.8	84.7	2.37	[152]
	2019	Im-bPPO	96.2	78.1	75.1	0.71	[153]
	2019	BPN1-100	97.9	83.7	81.9	2.6	[154]
	2019	*m*-TPN1	99.2	86.4	85.7	2.13	[154]
	2019	*p*-TPN1	99.6	86.4	86.0	2.15	[154]
	2020	M-PPFSt-MTZ-Me3	98.8	85.2	84.1	1.6	[155]
	2020	M-PPFSt-MTZ-Me4	99.9	71.7	71.6	1.15	[155]
	2020	PBI-GTA-112%	98.2	92.1	90.5	2.82	[156]
	2020	PBI-GTA-93%	97.8	90.6	88.6	2.39	[156]
	2020	PBI-GTA-67%	99.2	87.6	86.9	1.9	[156]
	2020	Py2-ADMPEK-1	99.7	83.3	83.1	2.14	[157]
	2020	Py2-ADMPEK-2	97.9	88.0	86.1	2.45	[157]
	2020	Py2-ADMPEK-3	98.6	89.5	88.2	2.59	[157]
	2021	VIMPPO_10%	94.9	73.8	70.0	n/a	[158]
	2021	VIMPPO_15%	97.5	76.5	74.6	n/a	[158]
	2021	VIMPPO_20%	97.6	68.4	66.8	n/a	[158]
	2021	DQA-TAPFE-20	95.1	84.4	80.3	1.55	[159]
	2021	PTP-CHPTMA	98.9	89.2	88.3	n/a	[160]
	2021	PBI-48% BPTMA	99.3	83.0	82.4	1.9	[161]
	2021	PAES-8mPip-0.20	96.7	84.2	81.3	1.49	[162]
	2021	PAES-8mPip-0.25	96.2	87.2	83.9	1.64	[162]
	2021	PAES-8mPip-0.30	93.4	87.4	81.6	1.78	[162]
	2021	QAPPEK-P-50	95.6	88.6	84.6	0.98	[163]
	2021	ImPEEK	98.4	86.2	84.9	2.16	[164]
	2021	ClmPEEK	98.5	87.2	85.9	2.04	[164]
	2021	PTP-QA	98.9	90.6	89.6	2.80	[165]
	2021	CMVI-C10	95.3	82.5	78.6	0.98	[165]
	2021	CMVI-C3	97.1	83.2	78.2	1.21	[165]
	2022	PAPI 2.5	96.8	85.0	82.2	1.51	[166]
	2022	PAPI 2.25	97.0	83.7	81.2	1.44	[166]
	2022	PTFE/PAPI 2.5	97.4	85.3	83.0	n/a	[166]
	2022	PAPI 2.0	97.5	82.5	80.4	1.38	[166]
	2022	PTFE/PAPI 2.25	97.6	84.1	82.2	n/a	[166]
	2022	PTFE/PAPI 2.0	97.9	83.6	81.9	n/a	[166]
Commercial AEM	2019	FAP 450	98.0	79.0	77.5	2.18	[152]
	2019	FAP 450	98.8	83.0	82.0	0.93	[154]
	2021	FAP 450	98.0	74.2	72.7	n/a	[158]
	2022	FAP 450	95.2	84.6	80.6	n/a	[166]
Nafion	2018	Nafion 115	97.0	86.0	83.4	>0.9	[149]
	2018	Nafion 117	93.6	84.0	78.6	>0.9	[148]
	2019	Nafion 117	83.0	76.5	63.5	>0.9	[150]
	2019	Nafion 212	87.9	92.0	80.8	>0.92	[151]
	2019	Nafion 212	96.0	86.9	83.4	>0.92	[152]
	2019	Nafion 212	90.1	92.4	83.2	>0.92	[153]
	2019	Nafion 212	91.5	86.8	79.5	>0.92	[154]
	2020	Nafion 212	95.6	87.0	83.1	>0.92	[155]
	2020	Nafion 212	88.9	90.5	80.4	>0.92	[156]
	2020	Nafion 212	85.6	90.3	77.3	>0.92	[157]
	2021	Nafion 115	98.1	76.2	74.8	>0.9	[158]
	2021	Nafion 115	97.5	83.3	81.3	>0.9	[160]

	2021	Nafion 115	97.6	79.2	77.3	>0.9	[161]
	2021	Nafion 115	94.4	88.1	83.1	>0.9	[163]
	2021	Nafion 115	97.4	78.8	76.8	>0.9	[165]
	2021	Nafion 117	94.0	81.4	79	>0.9	[167]
	2021	Nafion 212	91.3	87.9	80.2	>0.92	[159]
	2021	Nafion 212	95.4	85.9	82	>0.92	[162]
	2021	Nafion 212	93.5	81.9	76.6	>0.92	[164]
	2022	Nafion 115	90.4	86.9	78.5	>0.9	[166]
PBI	2020	O-PBI	99.5	79.3	78.9	n/a	[156]
	2022	gel-mPBI/py-PBI/gel-mPBI assembly	98.5	91.9	90.5	n/a	[168]
	2022	gel-mPBI/m-PBI/gel-mPBI assembly	98.6	91.3	90.0	n/a	[168]
	2022	gel-mPBI/PBI-OO/gel-mPBI assembly	99.9	89.3	89.3	n/a	[168]
	2023	p-OPBI/10x-OPBI/p-OPBI assembly	99.7	91.1	90.8	n/a	[169]

Table S11. Ion-pair HT-PEMFC durability of MEAs.

Year	Backbone	Cation group	IEC (meq uiv. g^{-1})	*t* (μm)	Ionomer	Ion-pair HT-PEMFC durability					Ref.
						Mode/Reactant gas	Temp (°C)	Initial V	Time (h)	Loss (%)	
2016	DAPP	BTMA	1.7	65	Styrene-BTMA	0.4 V/P_{H2O} = 9.7 kPa, H_2-air	120	0.22 A cm^2	500	0.33 mA cm^{-2} h^{-1}	[170]
2020	PSf	BTMA	1.8	77	PTFE	0.2 A cm^{-2}/ H_2-O_2	160	0.54	25	16 mV h^{-1}	[171]
2020	PolybenzIm		n/a	n/a	n/a	0.2 A cm^{-2}/H_2-O_2	160	0.69	390	0.1 mV h^{-1}	[172]
2020	PSf	Pyr	1.7	39	PSf-Pyr	0.2 A cm^{-2}/H_2-O_2	180-220	0.4	120	No degradation	[173]
2020	DAPP	Alkyl-A	1.8	40	Styrene-Phosphonic acid	0.6 A cm^{-2}/H_2-air	160	0.55	500	0.35 mV h^{-1}	[174]
2021	PolybenzIm		3.9	45	PTFE	0.4 A cm^{-2}/H_2-air	180	0.55	48	0.5 mV h^{-1}	[175]
2021	PolybenzIm		n/a	n/a	n/a	0.3 A cm^{-2}/H_2-air	160	0.65	200	No degradation	[176]
2022	FLN	Alkyl-A	1.84	52	PTFE	0.15 A cm^{-2}/H_2-O_2	140	0.67	60	0.2 mV h^{-1}	[177]
2022	Polyphenyl	DABCO	2.5	100	PTFE	0.3 V/8% RH/ H_2-O_2	160	1.7 A cm^{-2}	60	3.3 mA cm^{-2} h^{-1}	[178]
2022	DAPP	Alkyl-A	1.8	35	Nafion/Styrene-Phosphonic acid	0.6 A cm^{-2}/H_2-air	160	0.52	2,500	No degradation	[179]
2023	Phenyl-Pip		1.9	60	PTFE	0.2 A cm^{-2}/H_2-O_2	120	0.7	1,000	No degradation	[180]

Table S12. Performance and durability of CO_2 and CO electrolyzers.

Year	Membrane	Electrolyte	*i* (mA cm^{-2})	Main product	FE (%)	Device durability		Ref.
						hour	V	
2003	Selemion	0.2 M K_2SO_4	100	CO	> 50	n/a	n/a	[181]
2014	Fumasep	1 M KOH	250	Propyl alcohol	21	n/a	n/a	[182]
2014	Selemion	0.1 M $NaHCO_3$	10	CH_4	85	1	1.25	[183]
2016	n/a	0.1 M H_2SO_4	100	CO	92	250	3	[184]
2016	Fumatech	1 M KOH & 0.5 M $KHCO_3$	200	C_2H_2	46	n/a	n/a	[185]
2017	Sustainion	Deionized H_2O	140	Formic acid	94	550	3.4	[186]
2017	n/a	0.5 M $KHCO_3$	200	CO	64	n/a	n/a	[187]
2017	AMI-7001	0.01 M $KHCO_3$	200	CO	95	1,000	3.0	[188]
2017	AMI-7001	0.01 M $KHCO_3$	50	CO	90	4,380	3.0	[188]
2018	Fumatech	2.0 M KOH	630	C_2H_4	42	1	3.3	[189]
2018	n/a	1 M KHCO3	200	CO	90	n/a	n/a	[190]
2018	Fumatech	1 M KHCO3	145	$HCOO^-$	64	n/a	n/a	[191]
2018	PSMIM	0.5 M KHCO3	300	CO	90	8	2.75	[192]
2018	n/a	1.0 M KHCO3	450	C_2H_4	50	n/a	n/a	[193]
2018	n/a	0.1 M $KHCO_3$	450	C_2H_4	36	n/a	n/a	[194]
2018	Fumasep	1 M KOH	250	C_2H_4	18	n/a	n/a	[195]
2018	Fumasep	1 M $KHCO_3$	200	C_2H_4	30%	n/a	n/a	[196]
2019	Fumatech	0.1 M $CsHCO_3$	200	CO	60	n/a	n/a	[197]
2019	Sustainion	0.1 M $KHCO_3$	100	CO	80	135	3.75	[198]
2019	Sustainion	0.01 M $KHCO_3$	162	CO	97	10	3.0	[199]
2019	n/a	0.1 M $KHCO_3$	150	C_2H_4	46	100	4	[200]
2019	Sustainion	0.5 M $KHCO_3$	300	CO	99	9	2.6	[201]
2019	Fumasep	1 M KHCO3	250	EtOH	41	n/a	n/a	[202]
2019	Fumasep	3 M KHCO3	300	EtOH	41	12	3.7	[203]
2019	Selemion	1 M KHCO3	700	CO	85	10	3.75	[204]
2019	Fumatech	2.0 M KOH	450	AcO^-	48	n/a	n/a	[205]
2020	QAPPT	0.1 M $KHCO_3$ & 0.1 M KOH	350	CO	82	n/a	n/a	[206]
2020	PiperION	0.1 M CSOH	500	CO	80	100	3.2	[207]
2020	Fumasep	1 M $KHCO_3$	225	CH_4	73	n/a	n/a	[208]
2020	n/a	3.0 M Cs_2CO_3	200	CO	90	n/a	n/a	[209]
2020	Sustainion	1.0 M $KHCO_3$	200	$HCOO^-$	92	100	~2	[210]
2020	Sustainion	0.1 M $KHCO_3$	220	C_2H_4	69	100	3.8	[211]
2020	QAPPT	pure water	200	CO	90	100	2.3	[212]
2020	Selemion	0.5 M $KHCO_3$	400	CO	99	n/a	n/a	[213]
2020	Sustainion	1 M KOH	500	C_2H_4	33	n/a	n/a	[214]
2020	Fumasep	2 M KOH	180	AcO^-	42	n/a	n/a	[215]
2020	Sustainion	2 M $KHCO_3$	150	CO	55	n/a	n/a	[216]
2020	Sustainion	0.01 M $KHCO_3$	200	CO	82	n/a	n/a	[217]
2021	Aemion	1 M KOH	50	CO	>50	100	2.3-2.6	[218]
2021	Sustainion	1 M KOH or 1 M $KHCO_3$	150	CO	100	1.1	2.5	[218]
2021	Sustainion	0.1 M $KHCO_3$	100	C_2H_4	40	14	2.4	[219]
2021	Sustainion	0.1 M $KHCO_3$	300	EtOH	34	2	5-6	[220]
2021	Fumatech	1 M KOH	200	C_2H_4	40	n/a	n/a	[221]
2021	Sustainion	3 M KOH	150	C_2H_4	68	n/a	n/a	[222]
2021	Sustainion	1 M KOH	500	C_2H_4	n/a	110	2.8	[223]
2021	Fumasep & Sustainion	1M KOH	200	CO	69	5	2.6	[123]
2021	Fumasep	1 M KOH	65	$HCOO^-$	90	n/a	n/a	[224]
2021	Fumasep, G60	0.5 M $KHCO_3$	70	CO	78	10	2.12	[225]
2022	Fumasep, Neosepta	0.1 M KOH & 1.0 M $KHCO_3$	45	CO	n/a	16	4.1	[226]
2022	QAPPT	KOH, CsOH, $KHCO_3$	500	CO	78	100	3.3	[227]
2022	Sustainion	3 M KOH	100	C_2H_4	70	83	3.0	[228]
2022	SC-BPM	0.5 M K_2SO_4 & 0.1 M $KHCO_3$	200	C_2H_4	34	n/a	n/a	[229]
2022	Fumatech	pure water	100	CO	30%	0.5	3.7-3.9	[230]
2022	Fumasep	1 M $KHCO_3$	347	C_2H_4	30%	n/a	n/a	[231]
2022	Sustainion	2 M KOH	200	AcO^-	36	n/a	n/a	[232]
2022	Sustainion	0.1 M KOH	125	C_2H_4	68	5	3.5	[233]
2022	Sustainion	0.1 M KOH	n/a	CO	89	n/a	n/a	[234]

2022	Orion AMX	2 M KOH	200	acetate	44	120	2.2	[235]
2022	Fumasep	1 & 3 M $KHCO_3$	125	n/a	n/a	n/a	n/a	[236]
2023	Aemion	0.1 M $KHCO_3$	200	CO	96	200	3.1	[237]
2023	PVA/PQ44-OH	0.5 M $KHCO_3$	250	n/a	88	n/a	n/a	[238]
2023	Fumasep	1 M KOH	200	CO	~95	2	2.75-3.6	[239]
2023	Sustainion	1 M KOH	100	$HCOO^-$	92	8	2.1	[240]
2023	Selemion	0.1 M $KHCO_3$	700	C_2H_4	100	n/a	n/a	[241]
2023	Fumatech	0.1 M $KHCO_3$	200	C_2H_4	78	400	4.67	[242]
2023	Aemion	0.01 M $KHCO_3$	100	CO	90	100	3.0	[243]
2023	Radiation grafted ETFE	0.5 M $KHCO_3$	300	CO	90	n/a	n/a	[244]
2023	Radiation grafted ETFE	0.1 M $KHCO_3$	150	CO	80	200	3.1	[245]
2023	PVA & poly(diallyldimethylammonium)	0.5 M $KHCO_3$	18	$HCOO^-$	90	n/a	n/a	[246]
2023	Sustainion	0.1 M $KHCO_3$	300	CO	66	n/a	n/a	[247]
2023	PiperION	0.1 M $KHCO_3$	300	CO	40	10	3.05	[248]
2023	Sustainion	2 M KOH	300	CO	90	1	2	[249]

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