Supporting Information

Electricity-driven CO_2 and biomass conversion toward formic acid/formate: microenvironment regulation, hydrogen storage potential, and sustainability assessment

Shuai Liu,[†a] Deyu Wu,[†a] Dalin Sun,[a] Yan Zhang,[a] Heng Zhang,[*a] Tianyi Ma[*c] and Shuangyin Wang[*b]

[a] State Key Laboratory of Green Pesticide, State-Local Joint Laboratory for Comprehensive Utilization of Biomass, Center for R&D of Fine Chemicals of Guizhou University, Guiyang 550025, China

[b] State Key Laboratory of Chemo and Biosensing, College of Chemistry and Chemical Engineering, International Joint Lab of Energy Electrochemistry of the Ministry of Education, Hunan University, Changsha, Hunan, 410082 P. R. China

[c] Centre for Atomaterials and Nanomanufacturing (CAN), School of Science, RMIT University, Melbourne, VIC 3000, Australia

*Correspondence should be addressed to Heng Zhang: hzhang23@gzu.edu.cn; Tianyi Ma: tianyi.ma@rmit.edu.au; Shuangyin Wang: shuangyinwang@hnu.edu.cn.
[†] Contributed equally.

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Table S1. Various materials design engineering in electrocatalytic CO_2 production of formic acid/formate.

No.	Catalysts	Year	Stability (h)	DOI
1	Cu NWs-Bi NSs	2020	8	10.1016/j.jallcom.2020.155789
2	Ag-Bi@GF	2021	3.5	10.1016/j.electacta.2021.137821
3	Bi-Sn/CF	2018	100	10.1002/aenm.201802427
4	$In_{55}Cu_{45}$	2021	30	10.1021/acsami.1c07829
5	$In_{1.5}Cu_{0.5}$	2021	5	10.1016/j.apcatb.2020.119646
6	Ag/Sn-SnO_2NSs	2023	200	10.1007/s40820-023-01264-6
7	Pd_4Ag_1	2025	4	10.1039/D5DT00436E
8	NiO@Cl-9%	2022	24	10.1016/j.apmt.2022.101528
9	$Sn_3O(OH)_2Cl_2$	2023	40	10.1002/anie.202211174
10	$Co_{0.05}$-BOON	2024	100	10.1002/anie.202403671
11	Bi_4O_7/S	2024	40	10.1002/adfm.202403547
12	In-Bi_2O_3	2025	100	10.1002/anie.202423658
13	Zn_1Sn_1/SNC	2025	120	10.1038/s41467-025-57573-4
14	SAA-Zn_1Bi	2023	250	10.1016/j.apcatb.2023.123140
15	Bi-SA/NHCS	2023	10	10.1002/sstr.202300323
16	Ni NPs/MnO_2NDs-CFs	2018	11	10.1039/C8TA07687A
17	In/In_2O_{3-x}	2020	10	10.1016/j.scib.2020.04.022
18	Bimetallic Cu-Bi	2023	20	10.1002/anie.202217569
19	SnO_2/g-C_3N_4	2023	30.5	10.1021/acscatal.3c00688
20	$Bi_2O_2CO_3$/ZnO	2023	21	10.1007/s40843-022-2346-5
21	BiOI-C	2025	140	10.1016/j.apcatb.2025.125355
22	TA-Pb	2020	10	10.1038/s41467-020-17120-9
23	S_3-Cu_2O-70	2023	80	10.1002/adfm.202213145
24	β-Bi_2O_3	2025	100	10.1016/j.apcatb.2025.125302
25	Bi-CrO_x	2024	35	10.1002/anie.202415726
26	S2-In	2019	10	10.1038/s41467-019-08805-x

27	Sn−Pb−Sb	2019	16	10.1016/j.jcou.2019.03.016
28	MO_x@Cu_yO	2019	12	10.1021/acssuschemeng.9b04222
29	Cu foam@BiNW	2019	12	10.1039/C9EE00018F
30	Tin (Sn) nanoparticles	2018	48	10.1002/anie.201803501
31	Bi_2O_3/BiO_2	2022	30	10.1021/acs.nanolett.1c04683
32	Bi-NBs	2022	24	10.1002/adfm.202201125
33	Bi nanoparticles	2021	20	10.1016/j.cej.2020.127893
34	Bi_2O_3–CeO_x	2022	108	10.1021/acsmaterialslett.2c00512
35	BiO_x@C	2021	12	10.1016/j.electacta.2020.137478
36	In–O in In@InO_x	2022	25	10.1016/S1872-2067(21)63943-8
37	(Cu, N)-SnO_x	2020	24	10.1016/j.ces.2020.115947
38	Ag-In-S	2022	135	10.1002/adfm.202113075
39	M-AuPd	2021	6	10.1021/jacs.0c12696
40	s-SnLi	2021	150	10.1002/anie.202111351
41	Bi-MOF-TS	2025	24	10.1038/s41467-025-56975-8
42	GB-SnS	2025	150	10.1002/anie.202510973
43	$ZnO/ZnSnO_3$	2024	13	10.1002/cey2.444
44	CoPc/FePc HS	2021	10	10.1007/s40843-021-1749-5
45	V–Bi SAA	2023	90	10.1002/adma.202309648
46	Bi_2O_3-Bi_2S_3	2021	18	10.1002/smll.202105682
47	Bi NS-L	2025	30	10.1021/acs.nanolett.5c02163

Table S2. Various materials design engineering in electrocatalytic biomass production of formic acid/formate.

No.	Catalysts	Potential (V vs RHE)	Faradaic efficiency (%)	DOI
1	Pd-NiTe/NF	1.38	95.50%	10.1016/j.apcatb.2023.123236
2	$NiCo_2O_4$/NF	1.5	90%	10.1016/j.apcatb.2025.125355
3	Ni150s/NF	1.5	90.00%	10.1016/j.apcatb.2025.125211
4	PVP-$Ni(OH)_2$	1.3	93.70%	10.1016/j.apcatb.2025.125556
5	Pt@$Ni(OH)_{2-x}$	1.6	92%	10.1021/acscatal.4c07644
6	$Ni(OH)_2$/MnO@Ni	0.86	96%	10.1016/j.ijhydene.2024.06.140
7	SPA-$NiFeO_x$/$FeNi_3$	1.6	92.00%	10.1016/j.jechem.2025.05.015
8	$NiMoCo_{0.3}$	1.4	93.50%	10.1016/j.cej.2025.163901
9	Co,Cl-NiS	1.5	93.50%	10.1007/s40820-023-01181-8
10	CNFs@NiSe	1.62	99.94%	10.1039/C9TA09782A
11	Co_xP@NiCo-LDH/NF	1.35	100.00%	10.1016/j.jechem.2020.03.050
12	CuSA-Rh MAs/CF	1.5	96.5%	10.1038/s41467-023-41423-2
13	Pt-in-VGCC	1.26	79%	10.1002/adma.201804763
14	Ni-Mo-N/CFC	1.4	95.00%	10.1038/s41467-019-13375-z
15	$CuCo_2O_4$ nanosplates	1.3	89.1%	10.1021/acscatal.0c01498
16	CoS/Ni_3S_2/NF	1.32	95%	10.1016/j.apsusc.2025.163515
17	$CuCo_2O_{4-x}$ NSs	1.16	99%	10.1002/adma.202401857
18	NiCrO-$V_{Cr,O}$	1.45	96.00%	10.1021/acscatal.3c04568
19	$CuCo_2O_x$ (HVo-S)	1.36	98.50%	10.1021/jacs.5c03703
20	S-Cu-Ni/NF	1.35	98.12%	10.1021/acsami.5c03963
21	Cu-2NiOOH/NF	1.35	96.46%	10.1021/acs.inorgchem.4c03822
22	NiCoFeRuRe	1.133	95.60%	10.1002/anie.202501766
23	FeCoNiCuP	1.28	87.90%	10.1039/D4GC02517B
24	NiCoO-NS/NF	1.5	96.47%	10.1016/j.cej.2025.163249
25	$CuCo_2O_4$	1.4	98.00%	10.1039/D4TA05597G

26	D-CuCo/CoP/NF	1.4	90.30%	10.1002/adfm.202424311
27	MNFP-PNC/PCBC	1.34	86.10%	10.1016/j.seppur.2024.127178
28	Zn-Ni_3S_2/$Ni(OH)_2$/NF-KA	1.3	90.28%	10.1016/j.cej.2025.160396
29	Mn-doped Ni_7P_3	1.35	95.26 %	10.1016/j.jallcom.2025.179867
30	Pd doped Cu_3N	1.42	91.60%	10.1002/anie.202425006
31	CoNA-NiOH/NF-2	1.22	98%	10.1016/j.jcis.2024.11.194
32	Ni-MoO_2/NF	1.46	80.00%	10.1016/j.colsurfa.2025.136661
33	Fe-CuO_x/CF	1.33	93.65%	10.1016/j.apcatb.2024.124743
34	Ni/Fe ratio	1.5	98.50%	10.53941/see.2025.100003
35	NCO-CFP	0.99	98%	10.1016/j.cej.2024.150280
36	$CuNiO_{x\ r = 0.16}$|FTO	1.4	93.20%	10.1016/j.ijhydene.2025.150232
37	NiMnCu-LDH	1.5	95%	10.1016/j.ijhydene.2025.150434
38	Cu-MOF	1.44	90%	10.1073/pnas.2320777121
39	$Ni_{0.9}Mn_{0.1}$ LDH	1.5	85.8 %	10.1002/anie.202411517
40	Pd–PdS_2–Co_x	1.5	90%	10.1002/anie.202506032
41	Ni-MnO_2	1.16	99.7%	10.1007/s11426-025-2750-x
42	CuO-Co_3O_4	1.3	90.3%	10.1016/j.electacta.2023.143285
43	Ir-Co_3O_4	1.45	92%	10.1039/D2CC06931H
44	$Cu(OH)_2$/CF	1.2	84.5%	10.1016/j.jelechem.2024.118133
45	CoP	1.5	80%	10.1021/acscatal.2c02548
46	NiOOH@Ni_3S_2/NF	1.62	94%	10.26599/NR.2025.94907399
47	Sn-SnS_x	1.45	88%	10.1039/D4GC02203C
48	SnO_2/NF	1.48	99.8%	10.1016/j.cej.2025.165447

Table S3. Performance comparison of formic acid/formate prepared by CO_2RR, BEOR and CO_2RR/BEOR.

Item	Catalyst	Electrochemical cells	Duration of stability (h)	Current density [mA cm^{-2}]	Potential (V_{RHE})	Faradaic efficiency (%)	DOI
CO_2RR	nBuLi-Bi	Flow cell	100	450	-1.05	97	10.1038/s41467-020-17403-1
	$Bi_{0.1}Sn$	Flow cell	2400	100	-0.65	95	10.1038/s41467-021-25573-9
	Bi@$Bi_2O_2CO_3$	Flow cell	110	1200	-1.0	90	10.1016/j.nanoen.2023.108638
	Sn-Bi/SnO_2	MEA cell	2400	100	-4.1	95	10.1038/s41467-021-25573-9
	Bi_2S_3	Flow cell	100	2000	-0.95	93	10.1002/anie.202214959
	BiS-1	MEA cell	120	2000	-1.93	95	10.1002/anie.202408412
	In/N-dG	MEA cell	1200	520	−1.17	96	10.1002/anie.202307612
	Cl-SnO_2@Ni HF	Flow cell	520	3000	−2.69	64	10.1002/anie.202423370
	$Ga_{0.85}SnO_x$	Flow cell	4000	986	-1.63	82.9	10.1126/sciadv.adw7326
	$Sb_{0.1}Sn_{0.9}O_2$	MEA cell	200	1000	-3.6	92	10.1038/s44160-025-00769-9
	Co-N-COF	H-type	100	446	-1.05	97.4	10.1016/j.fuproc.2022.107451
	$Bi_{60}In_2O_{93}$	MEA cell	48	1000	-1.3	95.3	10.1016/j.apcatb.2023.123342
	CeO_x-Sn	Flow cell	108	444.4	-1.67	95	10.1002/smll.202400191
	BOC-NS	Flow cell	24	930	-1.55	93	10.1016/j.xcrp.2021.100353
	CDB	Flow cell	100	1100	-0.86	90	10.1002/aenm.202202818
	Bi_2O_3	MEA cell	1000	200	-3.6	91.3	10.1016/j.jcou.2020.101349
	$Bi_{19}Cl_3S_{27}$	Flow cell	30	400	-0.8	96	10.1002/ange.202407665
	GB-Bi	Flow cell	300	200	-3.8	70	10.1002/advs.202508152
	SnS NRs	Flow cell	48	722	-1.1	92	10.1021/acscatal.5c00213
	Bi(110)-S-Na	Flow cell	30	2505	-1.36	83.5	10.1016/j.chempr.2023.05.008
	Rh/In_2O_3	Flow cell	236	1200	-1.4	93	10.1021/acs.nanolett.5c01772
	Cu_6Sn_5	MEA cell	160	1200	-2.1	91	10.1038/s41467-024-45988-4
BEOR	Mn-Ni_7P_3/NF	H-type	100	270	1.3	95	10.1016/j.jallcom.2025.179867
	Ag_x-Pt_yPd_z	Flow cell	3000	400	1.2	-	10.1002/adfm.202418588
	Ru-CoP_2	H-type	180	500	1.34	87	10.1016/j.jechem.2024.08.056
	Cu-NiCo/NF	Flow cell	140	100	1.37	94	10.1002/anie.202411542
	CuO@CoOOH/CF	Flow cell	60	500	1.51	94	10.1016/j.apsusc.2025.163267
	$NiFe_2O_4$/NF	H-type	120	152	1.23	97	10.1016/j.cej.2023.143640
	NiS	Flow cell	25	400	1.34	90	10.1039/d5se00790a
	CoFe hydroxide	MEA cell	120	1000	2.05	90	10.1016/j.apcatb.2025.125811
	Co_3O_{4-x}@ZrO_{2-x}/NF	Flow cell	100	1000	1.5	90	10.1016/j.jcis.2025.138292

	$ZnCo_2O_4$ oxide/NF	Flow cell	230	1000	1.907	90	10.1021/acssuschemeng.5c03558
	NiVRu-LDHs NAs/NF	Flow cell	120	1000	1.933	80	10.1002/adma.202300935
	CuCoMo alloy	Flow cell	90	500	1.7	98.17	10.1021/acssuschemeng.5c04306
	CuNi	MEA cell	240	400	1.31	95.35	10.1021/acsnano.5c05973
	Ni_3N/Co_3N-NWs	Flow cell	200	1000	2.01	94.6	10.1002/adfm.202300547
	$Ni(OH)_2/NF$	H-type	40	500	1.6	90	10.1016/j.cej.2023.145292
	RuSA,NC/$Ni(OH)_2$	MEA cell	150	1000	1.4	94.3	10.1016/j.apcatb.2025.126067
	Ni-SAs/NOMC	MEA cell	100	800	2.6	95.4	10.1021/acsnano.5c03677
	$FeCoO_x$-2	H-type	80	100	1.38	100	10.1039/D5GC03013G
	NiOOH-Mo_2C@C	MEA cell	450	200	1.93	100	10.1002/ange.202506215
	FeCoNiMnMoO/NF	Flow cell	300	50	1.37	90	10.1016/j.apcatb.2025.125721
	NiMnCu-LDH	Single cell	120	100	1.36	95	10.1016/j.ijhydene.2025.150434
	P-NiFeOOH/NF	H-type	100	100	1.56	94.3	10.1002/advs.202412872
	NiCuO	H-type	24	100	1.39	94.6	10.1016/j.ces.2024.119937
	CuCoP/NF	H-type	100	100	1.24	85	10.1016/j.jallcom.2025.180847
	Co-$NiSe_2$/NF	H-type	20	200	1.41	90	10.1016/j.colsurfa.2025.138644
	FeNiCo LDHs	single cell	32	1000	1.38	-	10.1016/j.cej.2024.157435
	NiFe-sc-PBA	Flow cell	500	1500	1.625	98.5	10.1038/s41467-025-58203-9
	Ni/$Ni(OH)_2$-WO_2	H-type	90	325	1.78	-	10.1007/s12598-025-03544-z
CO_2RR//BEOR	Au/NiOOH@Ni	Flow cell	200	1200	3.14	180	10.1021/acscatal.4c01275
	Cu@CuS	Flow cell	12	800	3.37	175.8	10.1021/acs.jpclett.2c02180
	NCO-CFP	MEA cell	32	100	2.4	190	10.1016/j.cej.2024.150280
	$Sn_{76.8}Co_{23.2}$	H-type	56	16.3	1.5	160	10.1016/j.jallcom.2025.183366
	NiOOH@Ni_3S_2/NF	Flow cell	11	160	2.32	190	10.26599/NR.2025.94907399
	Rh/In_2O_3/CuAg/CF	Flow cell	22	500	2.1	190	10.1038/s41467-025-60008-9
	$Bi_2O_2CO_3$-CNT/$NiCo_2O_4$-CFP	Flow cell	32	100	2.4	196	10.1016/j.cej.2024.150280
	500-In_2O_3/NiV-LDH	Flow cell	48	700	4.97	189	10.1016/j.jechem.2025.01.041
	BiOCl/GDE/Cu_3Ag_7/CF	H-type	12	50	0.5	178	10.1002/anie.202516232
	$Sn_{76.8}Co_{23.2}$ /$Sn_{76.8}Co_{23.2}$	H-type	56	15	2.0	185	10.1016/j.jallcom.2025.183366
	CuBi/NiCo	H-type	20	10	2.07	192	10.1002/ange.202512078
	Bi/Bi_2O_3/Ni-$Bi(OH)_3$	H-type	250	120	3.0	160	10.1002/smll.202307741
	SnO_x@pCu@CF//pCu@CF	H-type	12	10	1.83	189	10.1016/j.ijhydene.2024.07.223
	Cu-CuO-Cu_2O NWs	H-type	100	100	2.382	200	10.1002/adfm.202314596
	Bi-$BiNiO_x$/NF/a β-$Ni(OH)_2$	H-type	90	10	1.76	180	10.26599/NR.2025.94908017

	Bi-BDC/Ni-BDC	Flow cell	24	65	2.4	180	10.1002/sstr.202500223

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Table S4. Performance comparison of CO_2-organic paired electrocatalysis.

Paired system	Anode catalyst	Cathode catalyst	Current density (mA cm^{-2})	Condition (V vs RHE)	Anode product and FE	Cathode product and FE	DOI
CO_2-HMF	CoS/Co-N-C	CoS/Co-N-C	100	1.69 V	FDCA; 98.2%	CO; 98.6%	10.1002/anie.202511448
	NiCo LDHs	Cu_1Bi	237	2.7 V	FDCA; 90%	FM; 90%	10.1039/D3EE01999C
	CuO-NF@Cu	Cu_2O/Cu-NF@GDL	188.8	2.75 V	FDCA; 96.6%	C_2H_4; 74.5%	10.1039/D3GC01420G
	$NiCo_2O_4$@NF	Bi NSs@CF	45	2.1 V	FDCA; 90.7%	FA; 85.1%	10.1002/ejic.202500133
	Fe_1Co_1/NF	Silver catalyst	100	-	FDCA; 89%	Syngas; 92%	10.1002/cssc.202502122
	PdO	PdO_x/ZIF-8	103.5	2.70 V	Organic acid; 84.3%	CO; 97.0%	10.1021/acssuschemeng.2c02117
	$Ni(OH)_2$/NF	Bi-In/C	11.58	2.06 V	FDCA; 88.2%	FM; 95.1%	10.1016/j.scib.2023.04.026
	FeNiCNTs/NF	FeNiCNTs/NF	11	2 V	FDCA; 99.6%	CO; 96.25%	10.1002/anie.202501404
	Ni-0.25EDTA2Na	Bi-EDTA2Na	100	2.65 V	FDCA; 90%	CO; 90%	10.1016/j.apcatb.2025.125146
	D-Co_3O_4	Ni-N-C	30	1.37 V	FDCA; 90%	CO; 90%	10.1002/cssc.202400493
	NiV	Ag/C	-	3.75 V	FDCA; 50%	Syngas; 80%	10.1002/adfm.202506183
	NiP@Ni/CF	Ag/CP	100	-	FDCA; 78%	CO; 95%	10.1039/D3SU00379E
	$Ni(OH)_2$/CP	Bi- MOFs	-	-1.2 V	FDCA; 75%	FA; 95.6%	10.1002/cctc.202201321
	Py-TEMPO	TBP-CoPc/CNTs	-	2.5 V	FDCA; 90.8%	CO; 96.9%	10.1039/D2CY01195F
	InOOH-O_V/NF	InOOH-O_V/C	-	2.27 V	FDCA; 91.6%	FA; 92.6%	10.1038/s41467-023-37679-3
	NiO NPs	BiOx	2	2.5 V	FDCA; 36%	FA; 81%	10.1021/acs.jpclett.0c00425
CO_2-Sulfide	p-Bi NSs	Co-S NSs	100	1.5 V	S_8; 92.9%	FA; 90%	10.1002/anie.202318585
	S-Cu:Co@NF	ER-Bi GDE	100	2.1 V	S_2^{2-};90%	FA; 95%	10.1016/j.apcatb.2023.122718
	v-$CuSe_2$	v-$CuSe_2$	200	1.92 V	S_8; 97.7%	CH_4; 58.9%	10.1002/smll.202411269
	CoPPc/NHCSs	CoPPc/NHCSs	118	1.5 V	S_8; -	CO; 97.23%	10.1016/j.checat.2023.100848
	G/GCS	rZnO@G	8.5	-	α-S; 99%	CO; 83%	10.1002/anie.201713029

	CoPPc/PNCA	CoPPc/PNCA	210	-	S; -	CO; 94%	10.1016/j.cej.2025.160286
	$(NH_x)_{16}$-NiPc/CNTs	$(NH_x)_{16}$-NiPc/CNTs	100	-1.55 V	S_8; 99%	CO; 99%	10.1002/adma.202202830
	NiNC-1000	NiNC-1000	200	2.6 V	SO_4^{2-};99%	CO; 93%	10.1016/j.cej.2025.163706
	BiOI	NiO/NF	10	1.8 V	SO_4^{2-};45%	FA; 90%	10.1021/acssuschemeng.2c03407
	Graphite Felt	CoPc GDE	50	-1.0 V	S; 99%	CO; 99.3%	10.1021/acs.est.1c04414
CO_2-Formaldehyde	Cu_2O	BiOCl	100	0.86 V	FA; 98.98%	FM; 90%	10.1007/s40820-022-00953-y
	CuAg/CF	Rh/In_2O_3	500	2.1 V	FA; 99%	FM; 91%	10.1038/s41467-025-60008-9
	Cu_3Ag_7/CF	BiOCl/GDE	10	0.5 V	FA; 96.1%	FM; 82.1%	10.1002/anie.202516232
	Cu	c-a Bi-NSs	44	2.0 V	FM; -	FM; 90%	10.1039/D3TA08011K
	Co/Mo-MOF	CuNi/NC-PS	100	1.95 V	FA; 97.4%	CO; 99.22%	10.1016/j.apsusc.2024.161864
CO_2-Chloride	Ni-CB	Ni-CB	100	3.8 V	Cl; 80%	CO; 98.5%	10.1016/j.apcatb.2020.119154
	OMP-CO_3O_4	OMP-Ni-N-C	20	2.5 V	ClO^-;87%	CO; 97%	10.1016/j.cej.2022.135500
	IrO_2	SnO_2	200	4.5 V	Cl_2; 95%	FA; 85%	10.1002/anie.202504782
	DSA	SnO_2	20	3.3 V	Cl_2; 60%	FA; 95%	10.1039/D1TA00285F
	IrO_2-Ta_2O_5/Ti	Bi_2O_3/CP	6.03	-1.01 V	ClO^-; 98%	FM; 98.7%	10.1016/j.seppur.2024.126592
	Blank GDL	Cu	100	2.15 V	ClO^-;85%	C_2H_4; 47%	10.1021/acs.jpclett.3c00179
	Pt	CoPc/g-C_3N_4	-	3 V	Cl_2; -	CO; 90.6%	10.1002/aenm.202100075
	RuO_2/Ti	Fe-Sas/N-C	-	2.0 V	ClO^-;92%	CO; 99.6%	10.1039/C9GC01099H
	Graphite Anode	Au Cathode	15.7	-2.241 V	Cl_2; 82.5%	CO; 92.23%	10.1016/j.electacta.2021.138728
CO_2-Urea	Ni-WOx	Ag/GDL	100	2.16 V	CO_2 or N_2; -	CO; 98%	10.1002/anie.202100610
	Ni foam	Ag/GDL	100	2.53 V	CO_2 or N_2; -	CO; 90%	10.1039/D0GC01754J
	$NiCoMoCuO_xH_y$	Cu	10	1.32 V	CO_2 or N_2; -	C_2H_4; 55%	10.1002/smll.202302151
	CuNi-CNT	CuNi-CNT	10	1.81 V	CO_3^{2-} or N_2; -	CO; 98.4%	10.26599/NR.2025.94907051
CO_2-NH_3	Pt/C	Au	10	2 V	H_2; 25.47%	CO; 73.87%	10.1016/j.cej.2021.132563

CO$_2$-CH$_4$	IrO$_2$	Bi	700	2.2 V	CH$_3$Cl; 34%	FA; 90%	10.1039/D4EE00087K
CO$_2$-Allyl alcohol	Ag	Pt	100	3.2 V	Acrolein; 85%	CO; 96%	10.1038/s41893-024-01363-1
CO$_2$-1,2-Propanediol	CF	Au/C	15	2.53 V	lactic acid; 80%	CO; 80%	10.1021/acs.iecr.8b06340
CO$_2$-Methanol	NiCo	CuBi	20	2.4 V	FA; 97.1%	FA; 94.8%	10.1002/anie.202512078
	Ni-2CBpy^{2+}-COF	Ni-2CBpy^{2+}-COF	12.65	1.9 V	FA; 97%	CO; 99%	10.1002/anie.202212162
	CuSn-4	CuSn-4	100	3 V	FA; 73.1%	FA; 81.7%	10.1016/j.nanoen.2022.107277
	Ni(OH)$_2$	Bi NPs	100	3 V	FA; 90%	FA; 99%	10.1016/j.cej.2020.127893
	Ni-SAs/NOMC@Ti	Ni-SAs/NOMC@GDE	500	2.7 V	FM; 95.4%	CO; 69.3%	10.1021/acsnano.5c03677
	Ni-Bi(OH)$_3$/NF	Bi/Bi$_2$O$_3$	10	2.31 V	FA; 98%	FA; 80%	10.1002/smll.202307741
	S-NiCo-LDH	BiPO$_4$	300	2.5V	FA; 90%	FA; 87.3%	10.1039/D1TA08303A
	Pt-WP/MWCNT	Fe-N-C	10	0.79 V	-	CO; 94.93%	10.1016/j.scitotenv.2024.174288
	NiCo-NF-ET	Ni-SAs@FNC	10	1.94 V	FA; 99%	CO; 80%	10.1002/sstr.202100134
	CuONS/CF	mSnO$_2$/CC	20	1.22 V	FA; 91.3%	FA; 80.5%	10.1002/anie.202012066
	Ni-NF-Af	Bi-ene(BDC)	100	1.35 V	FA; 99%	FA; 95%	10.1002/adma.202008631
	hydroxide@np-Ni$_3$P	InS NRS	50	2.29 V	FA; 98.1%	FA; 94.2%	10.1021/acsami.2c01152
	Cu-CuO-Cu$_2$O NWs	Bi NS	100	2.382 V	FM; 99%	FM;90%	10.1002/adfm.202314596
	Ni@HNC	Ni@HNC	11.1	2.7 V	FA; -	CO; 98.7%	10.1016/j.jece.2023.109427
	Cu$_{2-x}$Se@CuO/CF	Bi/BiO$_x$/CP	200	2.13 V	FA; 95%	FA; 96.1%	10.1002/anie.202412410
	Pd/MnFe$_2$O$_4$	Pd/MnFe$_2$O$_4$	227	1.0 V	CO$_2$; -	FA; 97.5%	10.1016/j.fuel.2021.122619
	Bi$_2$O$_3$-SnO@CuO	Bi$_2$O$_3$-SnO@CuO	38	3.0 V	FA; 97.5%	FA; 94.7%	10.1016/j.jcis.2023.08.196
	PVP@Cu$_2$O	PVP@Cu$_2$O	75	2 V	FA; 91%	FA; 88.2%	10.1021/acs.nanolett.2c01942
	Ni-MOFs@350	Ni&NiNC	500	2.4 V	FA; 98.4%	CO; 90%	10.1021/acscatal.2c05144
	NiO/CN/NF	a/c-BiB NAs/CF	7.5	2.0 V	FA; 93.3%	FA; 98.5%	10.1039/D3TA03918H
	NiPc-NiPor COF	NiPc-NiPor COF	10	2.3 V	FA; 93.75%	CO; 98.12%	10.1093/nsr/nwad226

	Ni_3N-Co_3N/NF	Vo-BOC-NS	50	2.27 V	FA; 95%	FA; 97%	10.1002/inf2.12375
	HOD-CuO	HOD-Cu	10	2.18 V	FA; 94%	FA; 63%	10.1016/j.xcrp.2022.100972
	PCN-601	PCN-601	5	1.99 V	FA; 90%	FA; 95%	10.1002/anie.202207282
	$Co(OH)_2$@HOS/CP	Bi-NSs	10	2.44 V	FA; 99%	FA; 90%	10.1002/asia.202100305
	$Ni(OH)_2$/NF	3D Bi-ene-A/CM	19	2.9 V	FA; 96.5%	FA; 91.4%	10.1002/smll.202105246
CO_2-Ethanol	$CuCo_2Se_4$	$CuCo_2Se_4$	50	0.78 V	Acetic acid; 71.35%	FA; 92.50%	10.1021/acsami.3c00488
CO_2-Ethylene glycol	3D Ni foam	$Bi_2O_2CO_3$	500	1.5 V	FA; 93.7%	FA; 86.0%	10.1021/jacs.5c11708
	CuCoO	$Bi_2O_2CO_3$	10	1.9 V	FA; 80.2%	FA; 71.6%	10.1039/D3TA05726G
	PdBiRh TML	PdBiRh TML	10	0.59 V	Glycolic acid; 91.19%	C_{2+}; 55.48%	10.1007/s11426-025-2721-0
	$Ni(OH)_2$-VO	Bi/Bi_2O_3	100	2.7 V	FA; 91.0%	FA; 90.0%	10.1021/acscatal.3c03428
	$NiCo_2O_4$/CFP	Sn&SnO_2/CC	30	1.9 V	FA; 85%	FA; 70%	10.1021/acscatal.2c01128
	Cr-Ni_3S_2-$Ni(OH)_2$/NF	Bi-MOF	400	2.7 V	FM; 96%	FM; 96.4%	10.1002/aenm.202504208
	$Ni(OH)_2$	10In-SnO_2/C	30	2.3 V	FM; 84.6%	FM; 81.5%	10.1016/j.apcatb.2025.125471
	NiOOH/$Ni_3Bi_2S_2$/NF	Bi	100	2.6 V	FM; 96%	FM; 97.1%	10.1016/j.cej.2024.155106
	Au/$Ni(OH)_2$	Bi	200	-	FA; 96.5%	FA; 90%	10.1007/s11426-023-1984-8
	$Cu(OH)_2$	$Cu(OH)_2$-D	100	1.3 V	FA; 89.5%	Ethylene; 60.8%	10.1002/smll.202502144
	CuO@$Ni(OH)_2$	Pb-SnO	10	1.63 V	FA; 62.0%	FA; 89.0%	10.1021/acssuschemeng.3c08233
	Mn/CoOOH	OV-rich BOC	150	2.2 V	FA; 94.2%	FA; 90.0%	10.1016/j.apcatb.2024.124667
	NiOOH/NF	Bi_2O_3	20	2.8 V	FA; 91.1%	FA; 93.7%	10.1016/j.cattod.2025.115544
CO_2-Benzylalcohol	SCB-8/NG	SCB-8/NG	300	1.8 V	Benzaldehyde; 93%	C_{2+}; 92.4%	10.1002/anie.202513840
	$Ni(OH)_2$	Cu_2O/Cu-0.7	10	1.75 V	Benzoic acid; 97.7%	C_{2+}; 85.5%	10.1016/j.cej.2024.149800
	pCu@CF	SnO_x@pCu@CF	10	1.73 V	Benzoic acid; 99%	FA; 89%	10.1016/j.ijhydene.2024.07.223
CO_2-Phenylethanol	Pt	Cu-In	3.7	-0.7 V	Acetophenone; 95%	CO; 70%	10.1021/acscentsci.7b00207
CO_2-Gycerol	NiCoP/NF	Bi NS-L	200	2.3 V	FM; -	FM; 93.9%	10.1021/acs.nanolett.5c02163

	AuIn	Bi/C-GDE	90	3.11 V	C_3; 95%	FM; 81%	10.1002/cssc.202402378
	NiV-LDH	500-In_2O_3	300	4.43 V	FA; 99.7%	FA; 94.5%	10.1016/j.jechem.2025.01.041
	Pt/C	Ag NPs	200	1.7 V	-	CO; 98%	10.1021/acscatal.3c05952
	Ag-Cu_6Sn_5	Ag-Cu_6Sn_5	10	2.28 V	FA; 86%	FA; 96.5%	10.1002/adma.202506697
	CuO@$CuNiBiO_x$	Sn	50	2.55V	FA; 89.6%	FA; 85%	10.1002/anie.202502617
	Ni_xB	BiOBr-GDE	50	3.04 V	FA; 45%	FA; 96%	10.1002/cssc.202202349
	Pt/C-PE	Bi-GDE	200	6.73 V	FA; 23%	FA; 44%	10.1016/j.jcou.2023.102431
	Ni-Co foam	Bi-C-GDE	45	3.4 V	FA; 55.4%	FA; 95.1%	/10.1016/j.cej.2023.147908
	$CoSe_2$/CC	NiSAs/FN-CNSs/CP	100	1.97 V	FM; 90%	CO; 90%	10.1016/j.nanoen.2021.106751
CO_2-Glucose	$Sn_{76.8}Co_{23.2}$	$Sn_{76.8}Co_{23.2}$	15	2.0 V	FA; 91%	FA; 96.3%	10.1016/j.jallcom.2025.183366
	Sn-SnS_x	Sn-SnS_x	12	1.8 V	FA; 87.4%	FA; 93.9%	10.1039/D4GC02203C
CO_2-Propylene	Pd/HMCs-10	Pd/HMCs-10	12	-0.6 V	PO; 47.11%	CO; 85.5%	10.1039/D5GC04779J
CO_2-Methyl orange	Ti/SnO_2-Sb anode	CNT40/ESGDE	40	-1.07 V	-	FA; 72.38%	10.1016/j.jcou.2018.05.027
	Ti/SnO_2-Sb	EBGDE-60	39	-1.07 V	-	FA; 91.46%	10.1016/j.electacta.2019.06.167
CO_2-Phenols	Ti/SnO_2-Sb	Cu/Bi	-	2.42 V	-	FA; 91.32%	10.1016/j.jcou.2021.101497
	Co_3O_4	CuO	-	-0.113 V	4-NP; 93%	C_2H_5OH; -	10.1016/j.watres.2018.11.077
CO_2-Hydrazine	ZnN_4S_1/P-HC	ZnN_4S_1/P-HC	5	1.2 V	N_2; -	CO; 99%	10.1002/adma.202209298
	$Ni_{SAs\text{-}NPs}$-N-HCSs	$Ni_{SAs\text{-}NPs}$-N-HCSs	100	1.98 V	N_2; 93.15%	CO; 98.98%	10.1016/j.cej.2023.148014
	Ni_2Fe_2N/NF	NiSACs-PCNF	100	0.45 V	N_2; -	CO; 98%	10.1016/j.apcatb.2024.124011

Table S5. Core challenges and engineering strategies in paired electrolysis.

Core challenge	Engineering strategy	Mechanism / principle	Current status & limitations
pH mismatch	Bipolar membrane (BPM)	Utilizes water dissociation at the interface to generate H^+ and OH^-, maintaining the Δ pH between the two sides.	Technology is relatively mature; exists ~0.8V additional voltage drop loss.
	Acidic CO_2 electrolysis	Cathode operates in an acidic environment, directly matching acidic anodic oxidation.	Thoroughly eliminates carbonates; HER competition is extremely strong, requiring special GDEs and high-concentration cations.
	pH-Universal catalysts	Develop materials stable across a wide pH range	Simplifies reactor design; currently, the types of selectable catalysts are limited.
Carbonate crossover	Acidic cathode	Thermodynamically inhibits CO_3^{2-} formation, directly reducing dissolved CO_2	Carbon efficiency is extremely high (>80%); long-term stability is a bottleneck.
	BPM in-situ regeneration	Utilizes the proton flux generated by the BPM to reduce crossover CO_3^{2-} back to CO_2	Capable of recovering the carbon source; needs to resolve membrane delamination issues caused by internal gas bubbles.
Mass-transfer imbalance	Pulsed electrolysis	Dynamic potential control, periodically refreshing the diffusion boundary layer.	Enhances limiting current density; power supply equipment is complex, difficult to scale up for large-scale application.
	Interdigitated flow field	Forced convection through electrode pores, strengthening liquid-phase mass transfer.	Significantly improves viscous liquid transport; increases pumping pressure energy consumption.
Electrode compatibility	Mediated oxidation	Uses redox mediators to avoid direct contact.	Prevents electrode poisoning; increases the complexity of downstream mediator separation.

Supplementary Note 1

To compare hydrogen transport using formic acid (HCOOH), ammonia (NH_3), and methylcyclohexane (MCH), we consider a typical liquid tanker load (≈25 tonnes of carrier). This allows us to estimate the hydrogen content delivered by one truck and the cost for a 500 km haul:

Transport Comparison (Per Truck)

Metric	HCOOH	NH_3	MCH
Carrier load per truck	~25 ton (≈20 m^3) formic acid	~25 ton (≈37 m^3) liquid ammonia	~25 ton (≈32 m^3) MCH (LOHC)
Hydrogen content per truck	~1,100 kg H_2 (at 4.4 wt% H_2 in HCOOH)	~4,400 kg H_2 (at 17.6 wt% H_2 in NH_3)	~1,500 kg H_2 (at 6.1 wt% H_2 in MCH)
Transport cost (500 km)	~\$0.5–0.8/kg H_2 (one-way) – moderate	~\$0.1–0.2/kg H_2 (one-way) – lowest	~\$0.4/kg H_2 one-way; ~\$0.8/kg H_2 if return trip for toluene
Return of carrier needed?	No (H_2 released to CO_2, tank returns empty)	No (H_2 released to H_2, tank returns empty)	Yes – after H_2 extraction, ~23 ton toluene must be shipped back

Ammonia can carry by far the most hydrogen per truck (over 4 tons H_2) due to its high hydrogen fraction and densitydthxyhg.com. In fact, 1 L of liquid ammonia contains ~50% more hydrogen than 1 L of liquid hydrogenrenewableinstitute.org. This gives ammonia the lowest transport cost per kg H_2 – on the order of just a few cents for hundreds of km. For example, a 240 km trip was estimated at \$0.18/kg for ammonia vs \$2.18/kg for compressed H_2 gasrenewableinstitute.org. Our 500 km estimate (~\$0.1–0.2/kg) similarly reflects ammonia's superior economics. Formic acid and MCH carry less hydrogen per load (~1.1 t and ~1.5 t respectively), so their trucking cost is higher (roughly \$0.5–0.8 per kg for formic, \$0.8 for MCH including return). Notably, MCH incurs extra logistic cost because the dehydrogenated carrier (toluene) must be hauled back to be reusedhydropowtech.com, effectively doubling the freight distance for each batch of hydrogen. Formic acid and ammonia do not require returning a heavy carrier (CO_2 and N_2 byproducts are simply released or handled on-site), so only an empty tanker returns. This gives formic acid a slight edge over MCH in one-way transport simplicity.

Safety and handling also differ: formic acid is a low-flammability, low-toxicity, making it relatively safe to transport in standard chemical tankers without pressure. Ammonia is toxic (and mildly pressurized at ambient temperature), requiring special tanks and safety measures, but is routinely transported in bulk as a commodity. MCH is a highly flammable liquid (flash point ≈ –4 °C) similar to gasoline, necessitating ADR class hazard precautions. Overall, formic acid offers safe, low-pressure hydrogen transport with decent H_2 payload, ammonia offers the highest payload and lowest cost (at the expense of toxicity and cracking requirements), and MCH has intermediate payload but higher logistic costs (due to return transport and handling of flammables).

We now compare hydrogen storage using each carrier versus conventional hydrogen gas storage. Storing hydrogen in chemical form allows ambient-temperature liquid tanks, whereas storing H_2 as a gas requires high-pressure vessels (e.g. spherical tanks). Below is a quantitative comparison assuming roughly 1,000 kg of H_2 stored in each form, highlighting storage capacity, tank cost, and footprint:

Storage Comparison (Tank Storage of Hydrogen)

Metric	HCOOH	NH_3	MCH	Compressed H_2 Gas
Hydrogen stored	1,000 kg H_2 (in ~23 t HCOOH)	1,000 kg H_2 (in ~5.7 t NH_3)	1,000 kg H_2 (in ~16.4 t MCH)	1,000 kg H_2 (as pressurized gas)

Required tank volume	~20 m^3 (ambient liquid tank)	~8–9 m^3 (pressurized or refrigerated)	~21 m^3 (ambient liquid tank)	>>100 m^3 gas volume (at high pressure)
Typical tank type	Stainless steel chemical tank (ambient pressure)	Spherical or cylindrical tank (mild pressurization or –33 °C refrigeration)	Carbon steel tank (ambient, like fuel storage)	High-pressure spherical vessel (e.g. 50–100 bar)
Tank capital cost	~$200k (e.g. 25 m^3 SS tank)	~$150k (e.g. 10 m^3 pressure tank)	~$100k (e.g. 25 m^3 CS tank)	$500k–$1,000k (thick-walled sphere)
Specific cost ($/kg H_2)	~$200/kg H_2 stored	~$150/kg H_2	~$100/kg H_2	$500–$1,000/kg H_2
Footprint (tank area)	~30–50 m^2 (incl. containment)	~20–30 m^2 (small tank, plus chilling unit)	~30–50 m^2 (incl. fire safety dike)	~50 m^2 tank base (sphere on legs)
Safety radius	Low: ~10–20 m (corrosive liquid, low flammability)	High: ≥50 m (toxic gas cloud & fire risk)	Moderate: ~30 m (flammable liquid fire zone)	High: ~50 m (flammable, high-pressure explosive)

Product Value vs Cost Considerations

Finally, we compare the market value of the hydrogen being moved or stored to the costs involved, to gauge the input–output economics:

Hydrogen value: Assuming a hydrogen price of $3 per kg, the hydrogen carried in one truck or stored in one tank is worth:

Formic acid truck: 1,100 kg H_2 ≈ $3,300 value

Ammonia truck: 4,400 kg H_2 ≈ $13,200 value

MCH truck: 1,500 kg H_2 ≈ $4,500 value

(For reference, a compressed H_2 tube trailer with ~250 kg H_2 is only ~$750 value

Transport cost vs value: For ammonia, the transport cost is trivial relative to hydrogen value – e.g. ~$0.15/kg on 4,400 kg is only ~$660, about 5% of the H_2 value. Formic acid's transport cost (~$0.6/kg) would consume ~20% of the hydrogen's $3/kg value. MCH's one-way cost (~$0.4) is ~13% of value; however, including the return trip (~$0.8/kg), over 25% of the hydrogen's value could go just into transportation. This shows a clear economic advantage for ammonia and formic acid in transport: ammonia delivers a high-value payload for little cost, and formic acid's safe one-way use avoids the doubled logistics that penalize the MCH route.

Storage cost vs value: Storing hydrogen as a commodity also shows better returns for liquid carriers. A tank of 1,000 kg H_2 as ammonia (~$3,000 worth of H_2) might cost on the order of $150k (tank), which is ~$150 per kg capacity – about 50 times the hydrogen's value. That sounds high, but hydrogen storage vessels are even worse: a high-pressure H_2 tank system at $500–1000/kg capacity. costs hundreds of times the H_2 value. In practice, such tanks would be used for many cycles over decades, but the upfront investment is large. Formic acid or MCH storage tanks, at ~$100–200/kg capacity, are relatively cheaper investments (still 30×–70× the hydrogen value in one fill). Importantly, formic acid offers a unique value.

Supplementary Note 2

1. Objective and system boundary definition objective:

To evaluate the economic potential of renewable-electricity-driven production of formic acid, we performed a plant-gate levelized cost techno-economic analysis (TEA) using a modified version of our previously reported model. The functional unit is 1 ton of commercial formic acid (85 wt% HCOOH) produced per day. The system boundary includes feedstock supply (CO_2 or selected biomass-derived feedstock), electrolyzer operation (cell stack, catalysts, membranes), downstream recovery (product extraction from electrolyte), and final thermal/electric concentration to 85 wt% HCOOH. Capital and operating cost assumptions for the base case are as follows:

(1) plant production capacity = 1 t (85 wt% HCOOH) day^{-1};

(2) total catalyst and membrane cost = 5% of the total electrolyzer capital cost;

(3) electrolyzer capital cost = \$10,000 m^{-2} of active electrode area (basis for area sizing and annualized CAPEX);

(4) electricity price (unless stated otherwise) = \$0.10 kWh^{-1} (conservative upper-bound for low-cost renewable electricity);

(5) separation & concentration costs are modeled as two components — (a) initial recovery of dissolved formate/formic acid from the electrolytic stream (liquid-liquid extraction / membrane recovery / electrodialysis) and (b) thermal/electric concentration to commercial 85 wt% product (multi-effect evaporation, vacuum distillation and/or membrane-evaporation hybrid). For the base case, combined separation + concentration energy and operating costs are initially assumed to equal 30% of the electricity cost, with the caveat that this fraction should be explored in sensitivity analysis because it strongly depends on feed concentration and choice of heat source;

(6) other operating costs (maintenance, labor, utilities excluding energy) = 10% of electricity cost;

(7) capacity factor = 0.8 (≈19.2 h day^{-1});

(8) electrochemical performance base case: Faradaic efficiency to formate/formic acid = 70%, cell voltage = 3.0 V, operating current density = 300 mA·cm^{-2} (these performance parameters should be varied to reflect current-state and future improvement scenarios);

(9) baseline market price for 85 wt% formic acid (for revenue sensitivity) = \$800 t^{-1} (range for sensitivity: \$600–\$1,200 t^{-1}); (10) co-product credits (e.g., H_2) are included when applicable using a baseline hydrogen price of \$1,900 t^{-1} and the actual measured Faradaic efficiency to H_2. All cost items (CAPEX amortization, catalyst replacement, balance-of-plant, separation equipment) follow the same equations and allocation methodology used in the referenced EO TEA model. Finally, we recommend presenting results for three scenarios — Worse / Base / Better — which vary electricity price (e.g., \$0.05–0.10–0.15 kWh^{-1}), Faradaic efficiency (40–70–90%), current density (50–300–1000 mA·cm^{-2}), cell voltage (5.0–3.0–2.5 V), and separation/concentration energy fraction (50%–30%–10% of electricity cost).

2. Economic assumptions and parameters

Parameter	Assumption or source	Value/range
Electricity price	Renewable electricity	0.05–0.10 \$·kwh^{-1}
Cell voltage	Industrial BEOR	3.0–4.0 v
Faradaic efficiency		70–90%
Current density		300–1000 ma·cm^{-2}
Electrolysis energy consumption	For liquid-phase formic acid	2.5–4.0 kwh·kg^{-1}
Catalyst lifetime		3–10 years
Electrolyzer cost		9000–11000 \$·m^{-2}
Separation cost	Fraction of electricity cost	20–30%
Thermal concentration energy	Literature average (>50% heat fraction)	3.5–5.0 mj·kg^{-1}
Market price of formic acid	Commercial grade (85 wt%)	800–1000 \$·t^{-1}

3. Energy and carbon emission analysis

Electrolysis energy (e_1):

$$E_1 = \frac{U \times I \times t}{m_{\mathrm{HCOOH}}} \approx 3.0\ \mathrm{kWh \cdot kg}^{-1}$$

(2) concentration energy (e_2):

1. Electrolyte product concentrations are typically 3–10 wt%.
2. Multi-effect evaporation or hybrid membrane–evaporation is required to reach 85 wt%.
3. Typical thermal energy demand ≈ 3.8 mj·kg^{-1} ≈ 1.06 kwh·kg^{-1}.
4. This accounts for approximately 25–35% of the total energy consumption.
5. If powered by fossil heat, it dominates the carbon footprint

(3) total energy consumption:

$$E_{total}=E_1+E_2=4.0\ \mathrm{kWh/kg}^{-1}$$

Assuming fully renewable electricity (0.05 kg co_2·kwh^{-1}):

$$0.05\times4\times1000=200\ \mathrm{kg\ CO_2/t}^{-1}$$

If the heat source is natural gas (0.2 kg co_2·mj^{-1}), concentration contributes an additional 700–900 kg CO_2·t^{-1},

Indicating that thermal concentration may dominate total carbon emissions (>70%), even with renewable electrolysis.

4. Cost breakdown

Cost component	Fraction (%)	Description
Electrolysis electricity	40–50	Major operational cost, highly sensitive to electricity price
Thermal concentration	20–30	Dependent on steam or electric heating source
Catalyst and electrolyzer depreciation	10–15	Determined by electrode area and lifetime
Electrolysis energy consumption	10	Includes membranes, pumps, and cooling systems
Feedstock (biomass)	5	Biomass waste may provide negative-cost scenarios

Estimated levelized cost:

Base case (current performance): 1200–1500 \$·t^{-1}

Optimistic case (≥1 a·cm^{-2} operation): 800–1000 \$·t^{-1}

Including full thermal concentration: adds ~20–25% to total cost unless waste heat is recovered.

5. Scenario and sensitivity analysis

Scenario	Electricity price (\$·kwh^{-1})	Concentration method	Feedstock type	Cost (\$·t^{-1})
A. Glycerol oxidation coupling	0.05	Waste-heat evaporation	Byproduct stream	~850
B. Glucose oxidation coupling	0.05	Electric evaporation	High-purity feedstock	~1250
C. CO_2 reduction only	0.10	Steam concentration	CO_2 feed (captured)	~1500

The results suggest that coupling with low-cost biomass byproducts (e.g., waste glycerol) and utilizing waste heat for concentration can reduce the levelized cost below the current market price of formic acid. In contrast, systems requiring high-purity feedstocks or additional concentration steps show limited economic viability.