POLITECNICO DI TORINO
Repository ISTITUZIONALE

CO2 valorisation towards alcohols by Cu-based electrocatalysts: challenges and perspectives

Original
CO2 valorisation towards alcohols by Cu-based electrocatalysts: challenges and perspectives / Hilmar, G., Russo, N., Simelys, H.. - In: GREEN CHEMISTRY. - ISSN 1463-9262. - ELETTRONICO. - 23:5(2021), pp. 1896-1920. [10.1039/d0gc03334k]

Availability:
This version is available at: 11583/2875982 since: 2021-03-23T16:43:06Z

Publisher:
RSC

Published
DOI:10.1039/d0gc03334k

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

14 September 2026

Electronic Supplementary Material (ESI) for Green Chemistry.
This journal is © The Royal Society of Chemistry 2021

CO_2 valorisation towards alcohols by Cu-based electrocatalysts: Challenges and perspectives

Hilmar Guzmán,[a,b] Nunzio Russo [a] and Simelys Hernández [a,b,*]

[a] *CREST group, Department of Applied Science and Technology (DISAT), Politecnico di Torino, C.so Duca degli Abruzzi, 24, 10129, Turin, Italy.*

[b] *IIT – Istituto Italiano di Tecnologia, Via Livorno, 60, 10144, Turin, Italy.*

* *Corresponding author. E-mail address:* simelys.hernandez@polito.it

Supporting Information

Summary

S1. CO_2-to-methanol via thermochemical route 2

S2. CO_2-to-methanol via liquid phase electrochemical route 3

S3. Total Faradaic efficiencies of the best liquid-phase EC CO_2R electrocatalysts 4

S4. Ethanol and n-propanol production from CO_2 via liquid-phase electrochemical route 5

S5. CO_2-to-alcohols via catholyte-free electrochemical route. 7

S6. Total Faradaic efficiencies of the best catholyte-free EC CO_2R electrocatalysts 9

S7. References 10

S1. CO_2-to-methanol via thermochemical route

Outstanding results following TC reactions for methanol production from our work1 with data taken from references2–[6.] Table S1 shows the best results following thermochemical reactions for methanol production.

Table S1**.** Outstanding results following TC reactions for methanol production from our work[1] with data taken from references[2–6].

Catalysts	CO_2 conversion, %	Selectivity Methanol, %	Temperature, °C	Pressure, MPa	Ref.
Cu/ZnO	5.5	50	240	2	[3]
Cu/ZrO_2	2.5	78	240	2	[3]
Cu/ZnO/Ga	6	88	270	2	[5]
Cu/ZrO_2/Ga	13.7	75.5	250	2	[5]
$Cu/ZnO/ZrO_2$	13	32	240	2	[3]
$Cu/ZnO/ZrO_2/SiO_2$	13.9	36	240	2	[4]
$Cu/ZnO/ZrO_2/TiO_2$	17.4	43.8	240	3	[2]
$Cu/ZnO/ZrO_2/Al_2O_3/SiO_2$	11.7	99.7	250	5	[6]

S2. CO_2-to-methanol via liquid phase electrochemical route

Table S2**.** State-of-the-art performance of the best catalysts to produce methanol from liquid-phase electrochemical CO_2 conversion.

Electrocatalysts	Faradaic efficiency to Methanol, %	Total current density, mA cm^{-2}	Cell configuration	Ref.
$Cu_{63,9}Au_{36,1}$/NCF	15.9	-	H-type cell (Nafion 117)	7
Anodiz. Cu foils	100.0	1.4	Traditional undivided 3 electrode cell	8
Electroch. Anodiz. Cu foils	20.0	5.0	Traditional undivided 3 electrode cell	
Cu_2O/stainless steel	38.0	5.0	Traditional undivided 3 electrode cell	
$Cu\backslash_{88}Sn_6Pb_6$ alloy foil	34.0	0.6	Two compartmentss (Nafion 117)	
Cu/Carbon paper	0.4	8.9	Two compartmentss (SPEEK)	
Electropolished Cu	0.1	10.0	Two compartmentss (AMV Selemion)	
Cu/ZnO	2.8	12.0	Two compartmentss (Nafion 117)	
Cu_2O /Carbon paper	20.0	2.4	Two compartmentss SPE (AMI-7001/ MEA)	
Cu/CuO	2.5	17.3	Two compartmentss (Nafion 117)	
Ru/Cu	42.0	0.1	Two compartmentss (agar bridge)	
Mo/Cu	84.0	0.8	Traditional undivided 3 electrode cell	
Cu_2O/ZnO	17.7	10.6	Two compartmentss (Nafion 117)	9
Cu-10-CNT/C	8.3	16.7	Two compartmentss (Nafion 117)	10
Cu_2O-MWCNTs	38.0	7.5	Two compartmentss (Nafion 117)	11
Oxide-der, Cu/ C (MOF)	18.0	1.0	Two compartmentss (Nafion 117)	12
CuO_x/ZnO	34.0	2.7	Traditional undivided 3 electrode cell	13
CuCNT-nanowires	47.4	0.9	Traditional undivided 3 electrode cell	14
CuCNT-Impregnation	23.3	0.9	Two compartmentss (Nafion 117)	14
Cu/Graphene	12.7	0.3	Two compartmentss (Nafion 117)	15
Cu/TiO_2/Graphene	19.5	0.3	Two compartmentss (Nafion 117)	15
Cu/Cu_2O	47.5	7.8	Two compartmentss (Nafion 117)	16
Cu-Y/CS:PVA MCE	68.0	0.3	Membrane coated electrode (MCE)	17
$Pd_{83}Cu_{17}$ Aerogels	80.0	31.8	H-type cell (Nafion 117)	18
$Cu_{1,63}Se_{1/3}$	77.6	41.5	H-type cell (Nafion 117)	19
CuSAs/TCNFs	44.0	93.0	H-type cell (Nafion 117)	20

S3. Faradaic efficiencies for different CO_2R products of the best liquid-phase electrocatalysts.

	Faradaic efficiency, % *											
Electrocatalysts	H_2	CO	C_2H_4	$HCOO^-$ /HCOOH	CH_3OH	C_2H_5OH	C_3H_8O	C_2H_6	CH_3COO^-	CH_4	J_{total}, mA cm^{-2}	Ref.
$Pd_{83}Cu_{17}$ Aerogels		<1.0			80.0						31.8	[18]
$Cu_{1.63}$Se1/3	<1.0	2.0	-	22.0	77.6	-	-	-	-	-	41.5	[19]
CuSAs/TCNFs	<1.0	54.0	-	-	44.0	-	-	-	-	-	93.0	[20]
Cu_2O					42.3	10.1	2.4				10.0	[43]
Cu_2O/ZnO					27.5	3.9	-				10.0	[43]
CuB_9 MOF	34.0	11.0	6.0	13.0	10.0	17.0	-	-	-	-	20.0	[33]
$CuBi_{12}$ MOF	30.0	9.0	7.0	16.0	9.0	28.0	-	-	-	-	20.0	[33]
B-OD-Cu	45.0	<1.0	20.0	5.0	-	20.0	-	8.0	-	-	33.4	[44]
Cu 25nm thickness	5.0	5.0	70.0	1.0	-	11.0	-	-	5.0	-	275.0	[35]
$Ag_{0.14}/Cu_{0.86}$ /PTFE	10.0	3.0	31.0	-	-	41.0	-	-	10.0	5.0	250.0	[36]
Electrodeposited CuAg alloy	9.8	6.5	55.2	3.0	-	25.9	2.4	-	1.6	1.6	300.0	[37]
Nanoporous Cu	7.6	14.7	38.6	1.9	-	16.6	4.5	-	2.2	-	653.0	[34]
Cu Nps/Carbon paper	10.6	38.9	35.0	7.6	-	11.2	2.1	-	0.4	-	430.0	[38]
Cu_2S–Cu-V	12.6	5.5	21.2	15.4	-	25.0	7.0	-	3.0	1.1	400.0	[39]
Ce(OH)x/Cu/PTFE	14.2	0.5	33.8	1.1	-	42.6	0.6	-	3.3	2.9	300.0	[45]
NGQ/Cu-nr	10.0	5.0	23.0	5.0	-	45.0	7.0	-	4.0	-	282.0	[46]
34% N-C/Cu/PTFE	7.4	0.3	37.5	1.7	-	52.3	1.4	-	2.3	1.2	300.0	[40]
$La_{1.8}SrO_{0.2}CuO_4$					2.0	30.5	10.0				180.0	[41]
Porous copper foam	69.2	4.6	4.0	5.9	-	3.2	4.9	2.8	0.7	-	37.5	[42]

Empty cells: no information available. (-) These products were not detected. * All values were approximated from the reported literature data.

S4. Ethanol and n-propanol production from CO_2 via liquid-phase electrochemical route

Table S3**.** State-of-the-art performance of the production of ethanol and n-propanol from liquid-phase electrochemical CO_2 conversion.

Electrocatalysts	Faradaic efficiency to Ethanol, %	Faradaic efficiency to n-Propanol, %	Total current density, mA cm^{-2}	Cell configuration	Ref.
Graphene/Cu_2O/Cufoil	9.9	-	5.3	Two compartments 3-electrodes cell separated by a glass frit	21
Cu(100)	9.7	1.5	5.0	Traditional undivided 3 electrode cell	22
Polycrystalline Cu	21.9	-	5.0	Two compartments separated by Selemion	23
3,6 μm film of Cu_2O	16.4	-	35.0	Two compartments separated by Selemion	24
CuO/TiO_2	37.5	5.6	8.3	H-type cell (Nafion 117)	25
$Cu_{63,9}Au_{36,1}$/NCF	12.0	-	-	H-type cell (Nafion 117)	7
Cu/N-Graphene	63.0	-	2.8	Two compartments separated by Selemion	26
Graphene/ZnO/Cu_2O/Cufoil	-	30.0	8.0	Two compartments cell separated by a glass frit	27
Cu nanocrystals	-	10.6	16.4	Two compartments separated by Selemion	28
Cu Nps/ Carbon paper x22.5 loading	13.3	5.9	12.7	Two compartments separated by Selemion	29
Cu/Graphene	24.1	3.1	1.3	Gas Diffusion electrode (Nafion 117)	30
CuO/TiO_2/Graphene	43.6	3.3	1.4	Gas Diffusion electrode (Nafion 117)	30
Cu_{1ML}/THH Pd NCs	20.4	-	0.6	H-type cell (Nafion 115)	31
Electrodeposited Cu onto Cu mesh	10.0	13.0	10.0 (normalized to the ECSA)	H-type cell (Nafion 117)	32
$CuBi_9$ MOF	17.0	-	20.0	Two compartmentss (Nafion 117)	33

$CuBi_{12}$ MOF	28.0	-	20.0	Two compartmentss (Nafion 117)	[33]
Nanoporous Cu	16.6	4.5	653.0	Gas Diffusion electrode	[34]
Cu 25nm thickness	11.0	-	275.0	Flow cell reactor	[35]
$Ag_{0,14}/Cu_{0,86}$ /PTFE	41.0	-	250.0	Gas Diffusion electrode	[36]
Electrodeposited CuAg alloy	25.0	-	300.0	Flow cell reactor	[37]
Cu Nps/Carbon paper	11.0	2.1	430.0	Flow cell reactor	[38]
Cu_2S–Cu-V	25.0	7.0	400.0	Gas Diffusion electrode	[39]
34% N-C/Cu/PTFE	52.0	1.0	300.0	Gas Diffusion electrode	[40]
$La_{1,8}Sr_{0,2}CuO_4$	30.5	10.0	180.0	H-cell	[41]
Porous copper foam	-	4.93	37.5	H-cell	[42]

S5. CO_2-to-alcohols via catholyte-free electrochemical route.

Table S4**.** State-of-the-art performance of the production of alcohols from solvent-less electrochemical CO_2 conversion .

Electrocatalysts	Relative FE to methanol, %	Relative FE to ethanol, %	Relative FE to n-Propanol, %	Total current density, mA cm^{-2}	Cell configuration	Ref.
Fe_{10}-CNTox/GDL	21.7	70.5	3.3	1.4	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[47]
Pt_{10}-CNTox/GDL	16.1	25.1	34.8	1.4	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[47]
Cu-Graphite/C	75.0	-	-	2.4	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[48]
Cu-AC/C	45.0	-	-	2.4	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[48]
Cu-CNF/C	2.5	2.0	2.5	2.4	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[48]
Cu-CNF/C (PBI)	5.0	2.0	0.2	1.6	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[49]
Cu powder	92.8	-	-	1.6	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[50]
Cu_C powder	14.1	-	-	1.6	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[50]
Cu Oxide/ZnO	0.2	0.2		7.5	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[51]
Pb/CNT	6.3	-	-	16.0	Continuous gas-phase	[52]

					CO_2 electroreduction. MEA Configuration.	
Cu(250nm)-C-G/PTFE	-	20.3	5.4	150.0	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[53]
Cu/TiO_2 NTs	23.5	-	-	120.0	Continuous Solid Polymer Electrolyte Membrane (SPE) Reactor	[54]
34% N-C/Cu/PTFE	-	56.5	2.7	160.0	Continuous gas-phase CO_2 electroreduction. MEA Configuration.	[40]
Commercial Cu_2O (solid-state electrolyte)	-	7.0	7.0	90.0	CO_2 electroreduction. MEA Configuration.	[55]

S6. Total Faradaic efficiencies of the best catholyte-free EC CO_2R electrocatalysts

	Relative Faradaic efficiency, %												
Electrocatalysts	CH_3OH	C_2H_4O	C_2H_5OH	C_3H_6O	C_3H_8O	CH_3COOH	CH_4	$C_2H_4O_2$	CO	C_2H_4	$HCOO^-$ /HCOOH	J_{total}, mA cm^{-2}	Ref.
Fe_{10}-CNTox/GDL	21.7	2.0	70.5	0.1	3.3	2.53	-	-	-	-	-	1.4	[47]
Pt_{10}-CNTox/GDL	16.1	19.8	25.1	0.2	34.8	4.1	-	-	-	-	-	1.4	[47]
Cu-Graphite/C	75.0	8.0	-	12.0	-	-	2.5	2.5	-	-	-	2.4	[48]
Cu-AC/C	45.0	48.0	-	5.0	-	-	1.0	1.0	-	-	-	2.4	[48]
Cu-CNF/C	2.5	70.0	2.0	-	2.5	-	5.0	12.0	10.0	-	-	2.4	[48]
Cu-CNF/C (PBI)	5.0	68.0	2.0	-	0.2	-	0.6	19.0	5.0	-	-	1.6	[49]
Cu_25nm powder	-	-	-	-	-	-	2.1	-	0.1	97.8	-	7.5	[56]
Cu powder	92.7	1.9	-	-	-	-	5.3	-	-	-	-	1.6	[50]
Cu_C powder	14.1	60.7	-	-	-	-	25.8	-	-	-	-	1.6	[50]
Cu Oxide/ZnO	0.2	-	0.2	0.2	-	-	0.5	-	0.3	98.5	-	7.5	[51]
Pb/CNT	6.3	-	-	-	-	-	34.4	-	9.4	-	50.0	16.0	[52]
Cu(250nm)-C-G/PTFE	-	-	20.3	-	5.4	6.7	-	-	13.5	54.1	-	150.0	[53]
Cu/TiO_2 NTs	23.5	-	-	-	-	-	17.6	-	58.8	-	-	120.0	[54]
34% N-C/Cu/PTFE	-	-	56.5	-	2.7	2.7	-	-	-	38.0	-	160.0	[40]
Commercial Cu_2O (solid-state electrolyte)	-	-	7.0	-	7.0	1.4	-	-	35.2	28.2	21.1	90.0	[55]

(-) These products were not detected.

S7. References

1 H. Guzmán, M. A. Farkhondehfal, K. Rodulfo Tolod, N. Russo and S. Hernández, in *Solar Hydrogen Production Processes, Systems and Technologies*, Elsevier Inc., 2019, p. 560.

2 J. Xiao, D. Mao, X. Guo and J. Yu, *Appl. Surf. Sci.*, 2015, **338**, 146–153.

3 T. Witoon, N. Kachaban, W. Donphai, P. Kidkhunthod, K. Faungnawakij, M. Chareonpanich and J. Limtrakul, *Energy Convers. Manag.*, 2016, **118**, 21–31.

4 T. Phongamwong, U. Chantaprasertporn, T. Witoon, T. Numpilai, Y. Poo-arporn, W. Limphirat, W. Donphai, P. Dittanet, M. Chareonpanich and J. Limtrakul, *Chem. Eng. J.*, 2017, **316**, 692–703.

5 S. Saeidi, N. A. S. Amin and M. R. Rahimpour, *J. CO2 Util.*, 2014, **5**, 66–81.

6 J. Toyir, R. Miloua, N. E. Elkadri, M. Nawdali, H. Toufik, F. Miloua and M. Saito, *Phys. Procedia*, 2009, **2**, 1075–1079.

7 F. Jia, X. Yu and L. Zhang, *J. Power Sources*, 2014, **252**, 85–89.

8 J. Albo, M. Alvarez-Guerra, P. Castaño and A. Irabien, *Green Chem.*, 2015, **17**, 2304–2324.

9 J. Albo, A. Sáez, J. Solla-Gullón, V. Montiel and A. Irabien, *Appl. Catal. B Environ.*, 2015, **176–177**, 709–717.

10 C. Genovese, C. Ampelli, S. Perathoner and G. Centi, *Green Chem.*, 2017, **19**, 2406–2415.

11 M. Irfan Malik, Z. O. Malaibari, M. Atieh and B. Abussaud, *Chem. Eng. Sci.*, 2016, **152**, 468–477.

12 K. Zhao, Y. Liu, X. Quan, S. Chen and H. Yu, *ACS Appl. Mater. Interfaces*, 2017, **9**, 5302–5311.

13 M. T. H. Le, Louisiana State University and Agricultural and Mechanical College, 2011.

14 B. C. Marepally, C. Ampelli, C. Genovese, F. Tavella, L. Veyre, E. A. Quadrelli, S. Perathoner and G. Centi, *J. CO2 Util.*, 2017, **21**, 534–542.

15 J. Yuan, M. P. Yang, Q. L. Hu, S. M. Li, H. Wang and J. X. Lu, *J. CO2 Util.*, 2018, **24**, 334–340.

16 J. Hazarika and M. S. Manna, *Electrochim. Acta*, 2019, **328**, 135053.

17 A. Marcos-Madrazo, C. Casado-Coterillo and Á. Irabien, *ChemElectroChem*, 2019, **6**, 5273–5282.

18 L. Lu, X. Sun, J. Ma, D. Yang, H. Wu, B. Zhang, J. Zhang and B. Han, *Angew. Chemie - Int. Ed.*, 2018, **57**, 14149–14153.

19 D. Yang, Q. Zhu, C. Chen, H. Liu, Z. Liu, Z. Zhao, X. Zhang, S. Liu and B. Han, *Nat. Commun.*, 2019, **10**, 1–9.

20 H. Yang, Y. Wu, G. Li, Q. Lin, Q. Hu, Q. Zhang, J. Liu and C. He, *J. Am. Chem. Soc.*, 2019, **141**, 12717–12723.

21 R. A. Geioushy, M. M. Khaled, A. S. Hakeem, K. Alhooshani and C. Basheer, 2017, **785**, 138–143.

22 Y. Hori, I. Takahashi, O. Koga and N. Hoshi, *J. Mol. Catal. A Chem.*, 2003, **199**, 39–47.

23 Y. Hori and R. Takahashi, 1989, **85**, 2309–2326.

24 D. Ren, Y. Deng, A. D. Handoko, C. S. Chen, S. Malkhandi and B. S. Yeo, *ACS Catal.*, 2015, **5**, 2814–2821.

25 J. Yuan, J. J. Zhang, M. P. Yang, W. J. Meng, H. Wang and J. X. Lu, *Catalysts*, 2018, **8**, 171.

26 Y. Song, R. Peng, D. K. Hensley, P. V. Bonnesen, L. Liang, Z. Wu, H. M. Meyer, M. Chi, C. Ma, B. G. Sumpter and A. J. Rondinone, *ChemistrySelect*, 2016, **1**, 6055–6061.

27 R. A. Geioushy, M. M. Khaled, K. Alhooshani, A. S. Hakeem and A. Rinaldi, *Electrochim. Acta*, 2017, **245**, 456–462.

28 D. Ren, N. T. Wong, A. D. Handoko, Y. Huang and B. S. Yeo, *J. Phys. Chem. Lett.*, 2016, **7**, 20–24.

29 D. Kim, C. S. Kley, Y. Li and P. Yang, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 10560–10565.

30 J. Yuan, M. P. Yang, Q. L. Hu, S. M. Li, H. Wang and J. X. Lu, *J. CO2 Util.*, 2018, **24**, 334–340.

31 F. Y. Zhang, T. Sheng, N. Tian, L. Liu, C. Xiao, B. A. Lu, B. Bin Xu, Z. Y. Zhou and S. G. Sun, *Chem. Commun.*, 2017, **53**, 8085–8088.

32 M. Rahaman, A. Dutta, A. Zanetti and P. Broekmann, *ACS Catal.*, 2017, **7**, 7946–7956.

33 J. Albo, M. Perfecto-Irigaray, G. Beobide and A. Irabien, *J. CO2 Util.*, 2019, **33**, 157–165.

34 J. J. Lv, M. Jouny, W. Luc, W. Zhu, J. J. Zhu and F. Jiao, *Adv. Mater.*, 2018, **30**, 1–8.

35 C. T. Dinh, T. Burdyny, G. Kibria, A. Seifitokaldani, C. M. Gabardo, F. Pelayo García De Arquer, A. Kiani, J. P. Edwards, P. De Luna, O. S. Bushuyev, C. Zou, R. Quintero-Bermudez, Y. Pang, D. Sinton and E. H. Sargent, *Science (80-.).*, 2018, **360**, 783–787.

36 Y. C. Li, Z. Wang, T. Yuan, D. H. Nam, M. Luo, J. Wicks, B. Chen, J. Li, F. Li, F. P. G.

De Arquer, Y. Wang, C. T. Dinh, O. Voznyy, D. Sinton and E. H. Sargent, *J. Am. Chem. Soc.*, 2019, **141**, 8584–8591.

37 T. T. H. Hoang, S. Verma, S. Ma, T. T. Fister, J. Timoshenko, A. I. Frenkel, P. J. A. Kenis and A. A. Gewirth, *J. Am. Chem. Soc.*, 2018, **140**, 5791–5797.

38 S. Ma, M. Sadakiyo, R. Luo, M. Heima, M. Yamauchi and P. J. A. Kenis, *J. Power Sources*, 2016, **301**, 219–228.

39 T. Zhuang, Z. Liang, A. Seifitokaldani, Y. Li, P. De Luna, T. Burdyny, F. Che, F. Meng, Y. Min, R. Quintero-bermudez, C. T. Dinh, Y. Pang, M. Zhong, B. Zhang, J. Li, P. Chen, X. Zheng, H. Liang, W. Ge, B. Ye, D. Sinton, S. Yu and E. H. Sargent, *Nat. Catal.*, 2018, **1**, 421–428.

40 X. Wang, Z. Wang, F. P. G. De Arquer, C. Dinh, A. Ozden, Y. C. Li, D. Nam, J. Li, Y. Liu, J. Wicks, Z. Chen, M. Chi, B. Chen, Y. Wang, J. Tam, J. Y. Howe, A. Proppe, P. Todorović, F. Li, T. Zhuang, C. M. Gabardo, A. R. Kirmani, C. Mccallum, S. Hung, Y. Lum, M. Luo, Y. Min, A. Xu, C. P. O. Brien, B. Stephen, B. Sun, A. H. Ip, L. J. Richter, S. O. Kelley, D. Sinton and E. H. Sargent, *Nat. Energy*, 2020, **5**, 478–486.

41 M. Schwartz, R. L. Cook, K. Victoria M., R. C. MacDuff, J. Patel and A. F. Sammells, *J. Electrochem. Soc.*, 1993, **140**, 614.

42 J. A. Rudd, E. Kazimierska, L. B. Hamdy, O. J. E. Bain, S. Ahn, A. R. Barron and E. Andreoli, *ChemRxiv*, , DOI:10.26434/chemrxiv.12022623.v1.

43 J. Albo and A. Irabien, *J. Catal.*, 2016, **343**, 232–239.

44 C. Chen, X. Sun, L. Lu, D. Yang, J. Ma, Q. Zhu, Q. Qian and B. Han, *Green Chem.*, 2018, **20**, 4579–4583.

45 M. Luo, Z. Wang, Y. C. Li, J. Li, F. Li, Y. Lum, D. H. Nam, B. Chen, J. Wicks, A. Xu, T. Zhuang, W. R. Leow, X. Wang, C. T. Dinh, Y. Wang, Y. Wang, D. Sinton and E. H. Sargent, *Nat. Commun.*, 2019, **10**, 1–7.

46 C. Chen, X. Yan, S. Liu, Y. Wu, Q. Wan, X. Sun, Q. Zhu, H. Liu, J. Ma, L. Zheng, H. Wu and B. Han, *Angew. Chemie*, 2020, **100049**, 16601–16606.

47 C. Genovese, C. Ampelli, S. Perathoner and G. Centi, *J. Catal.*, 2013, **308**, 237–249.

48 N. Gutiérrez-Guerra, L. Moreno-López, J. C. Serrano-Ruiz, J. L. Valverde and A. de Lucas-Consuegra, *Appl. Catal. B Environ.*, 2016, **188**, 272–282.

49 N. Gutiérrez-Guerra, J. L. Valverde, A. Romero, J. C. Serrano-Ruiz and A. de Lucas-Consuegra, *Electrochem. commun.*, 2017, **81**, 128–131.

50 N. Gutiérrez-Guerra, J. A. González, J. C. Serrano-Ruiz, E. López-Fernández, J. L. Valverde and A. de Lucas-Consuegra, *J. Energy Chem.*, 2019, 46–53.

51 I. Merino-Garcia, J. Albo, J. Solla-Gullón, V. Montiel and A. Irabien, *J. CO2 Util.*, 2019, **31**, 135–142.

52 J. García, C. Jiménez, F. Martínez, R. Camarillo and J. Rincón, *J. Catal.*, 2018, **367**, 72–80.

53 C. M. Gabardo, P. Colin, O. Brien, P. Jonathan, J. Li, H. Edward, D. Sinton, C. P. O. Brien, J. P. Edwards, C. Mccallum, Y. Xu, C. Dinh, J. Li, E. H. Sargent and D. Sinton, *Joule*, 2019, **3**, 2777–2791.

54 S. K. S. Hossain, J. Saleem, S. U. Rahman, S. M. J. Zaidi, G. McKay and C. K. Cheng, *Catalysts*, 2019, **9**, 1–19.

55 C. Xia, P. Zhu, Q. Jiang, Y. Pan, W. Liang, E. Stavitsk, H. N. Alshareef and H. Wang, *Nat. Energy*, 2019, **4**, 776–785.

56 I. Merino-Garcia, J. Albo and A. Irabien, *Nanotechnology*, 2018, **29**, 14001.