Prospects of green hydrogen in Poland: a techno-economic analysis using a Monte Carlo approach

Pablo Benalcazar*, Aleksandra Komorowska
Mineral and Energy Economy Research Institute of the Polish Academy of Sciences
Division of Energy Economics. ul. Wybickiego 7A, 31-261 Kraków, Poland

---

Appendix A. Supporting data

Data and references used to estimate the uncertainty distributions are provided in Table A.1–A.4

Table A.1: Electrolyzer costs.

Electrolyzer costs			
Value (€/kW)	**Year of estimate**	**Reference**	**Year of reference**
1,000	2015	[1]	2018
1,300	2017	[2]	2021
900	2017	[2]	2021
1,400	2017	[2]	2021
1,266	2017	[2]	2021
892.5	2020	[2]	2021
1,900	2010	[2]	2021
1,500	2017	[2]	2021
1,300	2014	[2]	2021
1,250	2017	[2]	2021
1,550	2017	[2]	2021
2,097.6	2017	[2]	2021
1,150	2017	[2]	2021
1,000	2017	[2]	2021
900	2014	[2]	2021
500	2020	[3]	2020
750	2019	[4]	2019
800	2020	[5]	2020
800	2020	[6]	2021
1,800	2020	[6]	2021
875.5	2020	[7]	2020
1,313.6	2020	[7]	2020
984,1	2020	[8]	2020
963,1	2020	[9]	2020
1,250.6	2019	[10]	2019
1,000	2020	[5]	2020
2,000	2020	[5]	2020
315.6	2030	[11]	2020
408.4	2030	[11]	2020
138.6	2050	[11]	2020
210.5	2050	[11]	2020

† Values presented in some reports are expressed in $/kW.
We use exchange rates published by Eurostat [12].

Table A.2: Levelized cost of electricity for onshore wind.

Levelized Cost of Electricity for Onshore Wind			
Value (€/kWh)	**Year of estimate**	**Reference**	**Year of reference**
0.05	2019	[13]	2020
0.0394	2020	[14]	2021
0.0829	2020	[14]	2021
0.04	2019	[15]	2020
0.04	2020	[15]	2020
0.0399	2018	[16]	2018
0.0823	2018	[16]	2018
0.04	2018	[17]	2019
0.08	2018	[17]	2019
0.05	2018	[18]	2019
0.065	2018	[18]	2019
0.025	2018	[19]	2021
0.026	2018	[19]	2021
0.028	2018	[19]	2021
0.030	2018	[19]	2021
0.030	2018	[19]	2021
0.031	2018	[19]	2021
0.032	2018	[19]	2021
0.033	2018	[19]	2021
0.035	2018	[19]	2021
0.035	2018	[19]	2021
0.036	2018	[19]	2021
0.038	2018	[19]	2021
0.040	2018	[19]	2021
0.041	2018	[19]	2021
0.045	2018	[19]	2021
0.047	2018	[19]	2021
0.047	2018	[19]	2021
0.049	2018	[19]	2021
0.049	2018	[19]	2021
0.050	2018	[19]	2021
0.054	2018	[19]	2021
0.057	2018	[19]	2021
0.058	2018	[19]	2021
0.061	2018	[19]	2021
0.062	2018	[19]	2021
0.065	2018	[19]	2021
0.066	2018	[19]	2021
0.077	2018	[19]	2021
0.079	2018	[19]	2021
0.096	2018	[19]	2021
0.119	2018	[19]	2021
0.131	2018	[19]	2021
0.040	2018	[20]	2021
0.051	2018	[21]	2019
0.025	2030	[11]	2020
0.042	2030	[11]	2020
0.017	2050	[11]	2020
0.025	2050	[11]	2020

† Values presented in some reports are expressed in $/kW.
Authors used exchange rates published by Eurostat [12].

Table A.3: Levelized cost of electricity for solar ground photovoltaic.

Levelized Cost of Electricity for Solar Ground PV			
Value (€/kWh)	**Year of estimate**	**Reference**	**Year of reference**
0.06	2019	[13]	2020
0.0312	2020	[14]	2021
0.057	2020	[14]	2021
0.04	2019	[15]	2020
0.03	2020	[15]	2020
0.031	2018	[16]	2018
0.067	2018	[16]	2018
0.029	2018	[19]	2021
0.029	2018	[19]	2021
0.030	2018	[19]	2021
0.032	2018	[19]	2021
0.033	2018	[19]	2021
0.035	2018	[19]	2021
0.037	2018	[19]	2021
0.037	2018	[19]	2021
0.039	2018	[19]	2021
0.040	2018	[19]	2021
0.043	2018	[19]	2021
0.047	2018	[19]	2021
0.049	2018	[19]	2021
0.053	2018	[19]	2021
0.053	2018	[19]	2021
0.068	2018	[19]	2021
0.073	2018	[19]	2021
0.074	2018	[19]	2021
0.076	2018	[19]	2021
0.082	2018	[19]	2021
0.146	2018	[19]	2021
0.050	2019	[20]	2020
0.072	2018	[22]	2019
0.017	2030	[11]	2020
0.068	2030	[11]	2020
0.008	2050	[11]	2020
0.042	2050	[11]	2020

† Values presented in some reports are expressed in $/kW.
Authors used exchange rates published by Eurostat [12].

Table A.4: Price of water.

Price of Water			
Value (€/kg)	**Year of estimate**	**Reference**	**Year of reference**
0.000934	2014	[23]	2014
0.000982	2015	[24]	2015
0.000965	2016	[25]	2016
0.000989	2017	[26]	2017
0.000988	2018	[27]	2018
0.001003	2019	[28]	2019
0.000999	2020	[29]	2020
0.000977	2021	[30]	2021
0.001280	2021	[31]	2021
0.001052	2021	[32]	2021
0.001089	2021	[33]	2021

Price of Water			
0.001107	2021	[34]	2021
0.001135	2021	[35]	2021
0.000942	2021	[36]	2021
0.000860	2021	[37]	2021
0.001043	2021	[38]	2021
0.001008	2021	[39]	2021
0.000950	2021	[40]	2021
0.000766	2021	[41]	2021
0.000757	2021	[42]	2021
0.001162	2021	[43]	2021
0.000869	2021	[44]	2021
0.000856	2021	[45]	2021
0.000882	2021	[46]	2021

† Prices of Water in Poland are expressed in PLN/m^3.
Authors used exchange rates published by Eurostat [12].

Appendix B. Supporting results

The merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for each scenario are provided in Table B.1–B.6

Table B.1: Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for ground solar PV (2020)

Ground Solar PV (2020)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL81	Lubelskie	12.64
PL72	Świętokrzyskie	12.73
PL52	Opolskie	12.76
PL41	Wielkopolskie	12.80
PL82	Podkarpackie	12.84
PL71	Łódzkie	12.87
PL21	Małopolskie	12.90
PL51	Dolnośląskie	12.93
PL22	Śląskie	12.93
PL43	Lubuskie	12.95
PL61	Kujawsko-pomorskie	12.98
PL91	Warszawski stołeczny	12.99
PL92	Mazowiecki regionalny	13.00
PL84	Podlaskie	13.19
PL42	Zachodniopomorskie	13.36
PL63	Pomorskie	13.47
PL62	Warmińsko-mazurskie	13.48

Table B.2: Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for ground solar PV (2030)

Ground Solar PV (2030)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL81	Lubelskie	4.12
PL72	Świętokrzyskie	4.13
PL52	Opolskie	4.15
PL41	Wielkopolskie	4.15
PL82	Podkarpackie	4.16
PL71	Łódzkie	4.17
PL21	Małopolskie	4.17
PL51	Dolnośląskie	4.17
PL22	Śląskie	4.18
PL43	Lubuskie	4.19
PL91	Warszawski stołeczny	4.19
PL92	Mazowiecki regionalny	4.20
PL61	Kujawsko-pomorskie	4.20
PL84	Podlaskie	4.24
PL42	Zachodniopomorskie	4.28
PL63	Pomorskie	4.30
PL62	Warmińsko-mazurskie	4.30

Table B.3: Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for ground solar PV (2050)

Ground Solar PV (2050)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL81	Lubelskie	1.95
PL72	Świętokrzyskie	1.96
PL52	Opolskie	1.96
PL41	Wielkopolskie	1.97
PL82	Podkarpackie	1.97
PL21	Małopolskie	1.97
PL51	Dolnośląskie	1.97
PL71	Łódzkie	1.97
PL22	Śląskie	1.97
PL43	Lubuskie	1.98
PL91	Warszawski stołeczny	1.98
PL61	Kujawsko-pomorskie	1.98
PL92	Mazowiecki regionalny	1.98
PL84	Podlaskie	2.00
PL42	Zachodniopomorskie	2.02
PL63	Pomorskie	2.03
PL62	Warmińsko-mazurskie	2.03

Table B.4: Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for onshore wind (2020)

Onshore Wind (2020)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL63	Pomorskie	6.37
PL42	Zachodniopomorskie	6.55
PL62	Warmińsko-mazurskie	7.07
PL61	Kujawsko-pomorskie	7.16
PL84	Podlaskie	7.28
PL51	Dolnośląskie	7.44
PL52	Opolskie	7.44
PL41	Wielkopolskie	7.69
PL91	Warszawski stołeczny	7.85
PL92	Mazowiecki regionalny	7.85
PL71	Łódzkie	8.01
PL81	Lubelskie	8.02
PL43	Lubuskie	8.02
PL72	Świętokrzyskie	8.60
PL21	Małopolskie	9.66
PL22	Śląskie	9.67
PL82	Podkarpackie	9.70

Table B.5Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for onshore wind (2030)

Onshore Wind (2030)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL63	Pomorskie	2.33
PL42	Zachodniopomorskie	2.37
PL62	Warmińsko-mazurskie	2.48
PL61	Kujawsko-pomorskie	2.50
PL84	Podlaskie	2.52
PL51	Dolnośląskie	2.56
PL52	Opolskie	2.56
PL41	Wielkopolskie	2.61
PL91	Warszawski stołeczny	2.65
PL92	Mazowiecki regionalny	2.65
PL71	Łódzkie	2.68
PL81	Lubelskie	2.68
PL43	Lubuskie	2.69
PL72	Świętokrzyskie	2.81
PL22	Śląskie	3.04
PL21	Małopolskie	3.05
PL82	Podkarpackie	3.06

Table B.6Merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) fonshore wind (2050)

Onshore Wind (2050)		
NUTS-2 Code	**Name**	**LCOH (€/kg)**
PL63	Pomorskie	1.23
PL42	Zachodniopomorskie	1.24
PL62	Warmińsko-mazurskie	1.29
PL61	Kujawsko-pomorskie	1.29
PL84	Podlaskie	1.30
PL51	Dolnośląskie	1.31
PL52	Opolskie	1.32
PL41	Wielkopolskie	1.33
PL92	Mazowiecki regionalny	1.35
PL91	Warszawski stołeczny	1.35
PL71	Łódzkie	1.36
PL81	Lubelskie	1.36
PL43	Lubuskie	1.36
PL72	Świętokrzyskie	1.41
PL21	Małopolskie	1.49
PL22	Śląskie	1.49
PL82	Podkarpackie	1.50

References:

[1] M. Kopp, *Stommarktseitige Optimierung des Betriebs einer PEM-Elektrolyseanlage*. Germany: Kassel University Press GmbH, 2018.

[2] Postdam Institute for Climate Impact Research, "Price of Hydrogen: CAPEX data," 2020. [Online]. Available: https://h2.pik-potsdam.de/H2Dash/?s=09#section-data. [Accessed: 06-Jul-2021].

[3] J. Proost, "Critical Assessment of the Production Scale Required for Fossil Parity of Green Electrolytic Hydrogen," *Int. J. Hydrogen Energy*, vol. 45, no. 35, pp. 17067–17075, Jul. 2020, doi: 10.1016/J.IJHYDENE.2020.04.259.

[4] J. Proost, "State-of-the art CAPEX Data for Water Electrolysers, and their Impact on Renewable Hydrogen Price Settings," *Int. J. Hydrogen Energy*, vol. 44, no. 9, pp. 4406–4413, Feb. 2019, doi: 10.1016/J.IJHYDENE.2018.07.164.

[5] IEA, "Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the Techno-Economic, Legal and Regulatory Conditions," 2020. [Online]. Available: https://www.ieahydrogen.org/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=17&wpfd_file_id=3572&token=abad9fa9a0f0a9c00152edff03825bf4&preview=1. [Accessed: 07-Jul-2021].

[6] Deloitte, "Fueling the Future of Mobility: Hydrogen Electrolyzers," 2021. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/jp/Documents/international business support/gbs/jp-gbs-fueling the future of mobility-hydrogen electrolyzers.pdf. [Accessed: 07-Jul-2021].

[7] Department of Energy of the United States of America, "Cost of Electrolytic Hydrogen Production with Existing Technology," 2020. [Online]. Available: https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf. [Accessed: 08-Aug-2021].

[8] Energy and Environmental Economics, "Hydrogen Opportunities in a Low-Carbon Future," 2020. [Online]. Available: https://www.ethree.com/wp-content/uploads/2020/07/E3_MHPS_Hydrogen-in-the-West-Report_Final_June2020.pdf. [Accessed: 08-Sep-2021].

[9] IEA, "The Future of Hydrogen," 2019. [Online]. Available: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. [Accessed: 05-May-2021].

[10] A. Christensen, "Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe," *International Council on Clean Transportation (ICCT)*, 2020. [Online]. Available: https://theicct.org/sites/default/files/publications/final_icct2020_assessment_of_hydrogen_production_costs v2.pdf. [Accessed: 08-May-2021].

[11] IRENA, "Green Hydrogen Cost Reduction," 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf. [Accessed: 05-May-2021].

[12] Eurostat, "EURO/ECU Exchange Rates in 2011-2020," 2021. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/ert_bil_eur_a/default/table?lang=en. [Accessed: 20-Jul-2021].

[13] IRENA, "Renewable Power Generation Costs in 2019," 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf. [Accessed: 15-May-2021].

[14] Fraunhofer Institute, "Stromgestenhungskosten Erneuerbare Energien," 2021. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2021_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf. [Accessed: 08-Aug-2021].

[15] Lazard, "Lazard's Levelized Cost of Energy Analysis - Version 14.0," 2020. [Online]. Available: https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf. [Accessed: 07-Jul-2021].

[16] Fraunhofer Institute, "Levelized Cost of Electricity Renewable Energy Technologies," 2018. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf. [Accessed: 09-Aug-2021].

[17] National Renewable Energy Laboratory, "2018 Cost of Wind Energy Review," 2019. [Online]. Available: https://www.nrel.gov/docs/fy20osti/74598.pdf. [Accessed: 12-May-2021].

[18] Wind Europe, "Wind Energy is the Cheapest Source of Electricity Generation," 2019. [Online]. Available: https://windeurope.org/policy/topics/economics/. [Accessed: 16-Aug-2021].

[19] IEA, "Levelized Cost of Electricity Calculator," 2021. [Online]. Available: https://www.iea.org/articles/levelised-cost-of-electricity-calculator. [Accessed: 20-Jul-2021].

[20] E. Ahmadi, B. McLellan, S. Ogata, B. Mohammadi-Ivatloo, and T. Tezuka, "An Integrated Planning Framework for Sustainable Water and Energy Supply," *Sustainability*, vol. 12, no. 10, p. 4295, May

2020, doi: 10.3390/su12104295.
[21] IRENA, “Future of Wind,” 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf. [Accessed: 06-May-2021].
[22] IRENA, “Future of Solar PV,” 2019. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf. [Accessed: 03-May-2021].
[23] Waterworks Kraków, “Price of Water in Kraków in 2014,” 2014. [Online]. Available: https://www.bip.krakow.pl/?dok_id=167&sub_dok_id=167&sub=uchwala&query=id%3D19972%26typ%3Du%0A. [Accessed: 20-Jul-2021].
[24] Waterworks Kraków, “Price of Water in Kraków in 2015,” 2015. [Online]. Available: https://www.bip.krakow.pl/zalaczniki/dokumenty/n/157101/karta%0A. [Accessed: 20-Jul-2021].
[25] Waterworks Kraków, “Price of Water in Kraków in 2016,” 2016. [Online]. Available: https://www.bip.krakow.pl/?dok_id=167&sub_dok_id=167&sub=uchwala&query=id%3D21158%26typ%3Du%0A. [Accessed: 20-Jul-2021].
[26] Waterworks Kraków, “Price of Water in Kraków in 2017,” 2017. [Online]. Available: https://www.bip.krakow.pl/?dok_id=167&sub_dok_id=167&sub=uchwala&query=id%3D21910%26typ%3Du%0A. [Accessed: 20-Jul-2021].
[27] Waterworks Kraków, “Price of Water in Kraków in 2018,” 2018. [Online]. Available: https://www.bip.krakow.pl/?dok_id=167&sub_dok_id=167&sub=uchwala&query=id%3D22876%26typ%3Du%0A. [Accessed: 20-Jul-2021].
[28] Waterworks Kraków, “Price of Water in Kraków in 2019,” 2019. [Online]. Available: https://www.bip.krakow.pl/zalaczniki/dokumenty/n/273099/karta%0A. [Accessed: 20-Jul-2021].
[29] Waterworks Kraków, “Price of Water in Kraków in 2020,” 2020. [Online]. Available: https://wodociagi.krakow.pl/admin/files/Files/cennik_i_taryfa/WMK-taryfa_24-05-2020r-23-05-2021r.pdf%0A0A. [Accessed: 20-Jul-2021].
[30] Waterworks Kraków, “Price of Water in Kraków in 2021,” 2021. [Online]. Available: https://wodociagi.krakow.pl/strefa-klienta/taryfa-i-cenniki.html%0A. [Accessed: 20-Jul-2021].
[31] Waterworks Katowice, “Price of Water in Katowice in 2021,” 2021. [Online]. Available: https://www.wodociagi.katowice.pl/strefa-klienta-wodociagi-katowice/ceny-wody-i-odprowadzania-sciekow%0A. [Accessed: 20-Jul-2021].
[32] Waterworks Poznań, “Price of Water in Poznań in 2021,” 2021. [Online]. Available: https://bip.poznan.pl/bip/aktualnosci/nowa-taryfa-oplat-za-wode-i-scieki,119325.html%0A. [Accessed: 20-Jul-2021].
[33] Waterworks Szczecin, “Price of Water in Szczecin in 2021,” 2021. [Online]. Available: https://zwik.szczecin.pl/klienci/faktury_i_rozliczenia/aktualne-taryfy-i-opaty%0A. [Accessed: 20-Jul-2021].
[34] Waterworks Zielona Gora, “Price of Water in Zielona Góra in 2021,” 2021. [Online]. Available: https://www.zwik.zgora.pl/strefa-klienta/taryfy-za-wode-i-scieki/aktualne-taryfy/%0A. [Accessed: 20-Jul-2021].
[35] Waterworks Wroclaw, “Price of Water in Wrocław in 2021,” 2021. [Online]. Available: https://mpwik.wroc.pl/strefa-klienta/taryfy-i-cenniki/%0A. [Accessed: 20-Jul-2021].
[36] Waterworks Opole, “Price of Water in Opole in 2021,” 2021. [Online]. Available: https://wikopole.com.pl/download/attachment/9382/taryfa-obowiazujaca-od-28102020-r-opole-i-gminy-oscienne.pdf%0A. [Accessed: 20-Jul-2021].
[37] Waterworks Toruń, “Price of Water in Toruń in 2021,” 2021. [Online]. Available: https://www.wodociagi.torun.com.pl/bok-cennik%0A. [Accessed: 20-Jul-2021].
[38] Waterworks Olsztyn, “Price of Water in Olsztyn in 2021,” 2021. [Online]. Available: https://pwik.olsztyn.pl/nowe-stawki-oplat-od-14-czerwca-2019-r%0A. [Accessed: 20-Jul-2021].
[39] Waterworks Gdańsk, “Price of Water in Gdańsk in 2021,” 2021. [Online]. Available: https://www.sng.com.pl/Portals/2/dok/Taryfy/GD.RZT.70.195.347.2021.D.JM.pdf?ver=2021-02-23-143511-077%0A. [Accessed: 20-Jul-2021].
[40] Waterworks Łódź, “Price of Water in Łódź in 2021,” 2021. [Online]. Available: https://zwik.lodz.pl/pl/artykuly/242/oplaty-od-13-06-2018-do-12-06-2021%0A. [Accessed: 20-Jul-2021].
[41] Waterworks Kielce, “Price of Water in Kielce in 2021,” 2021. [Online]. Available: https://wod-kiel.com.pl/temp/zdjecia_kat/40/oplaty_woda_scieki.pdf%0A. [Accessed: 20-Jul-2021].
[42] Waterworks Lublin, “Price of Water in Lublin in 2021,” 2021. [Online]. Available: http://www.mpwik.lublin.pl/index.php?option=site&id=3&sid=13%0A. [Accessed: 20-Jul-2021].

[43] Waterworks Przemyśl, “Price of Water in Przemyśl in 2021,” 2021. [Online]. Available: https://mpwik.sni.pl//imgs_upload2/ogloszenia/Taryfa Lublin 2018.pdf%0A. [Accessed: 20-Jul-2021].
[44] Waterworks Białystok, “Price of Water in Białystok in 2021,” 2021. [Online]. Available: https://www.wobi.pl/images/aktualnosci/BI_RET_070_684_2018_IT.pdf%0A. [Accessed: 20-Jul-2021].
[45] Waterworks Warszawa, “Price of Water in Warszawa in 2021,” 2021. [Online]. Available: https://warszawa19115.pl/-/nizsza-taryfa-za-wode-i-scieki-dla-mieszkancow-warszawy-i-okolic-od-2-czerwca-2018-r-%0A. [Accessed: 20-Jul-2021].
[46] Waterworks Radom, “Price of Water in Radom in 2021,” 2021. [Online]. Available: https://www.woda.radom.pl/index.php/cennik-i-taryfy/%0A. [Accessed: 20-Jul-2021].