Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supporting Information

Table S1: A summary of recent hydrogen production costs via SMR available in the literature. All costs have been converted to 2016 USD using the CEPCI.

Study	**Year of Study**	**Capital Cost Million $[b]**	**Plant Size**	**Natural Gas Price $ GJ^{-1}**	**Hydrogen Cost $ $kg^{-1}H_2$ ($ GJ^{-1})[a]**
National Research Council [1] (current)	2004	555.5	1,200 tpd H_2	5.22	1.26 (8.89)
National Research Council [1] (future)	2004	400.5	1,200 tpd H_2	5.22	1.33 (7.94)
NREL [2]	2009	208.9	379 tpd H_2	7.47	1.54 (10.84)
NREL [3]	2013	22.5	379 tpd H_2	6.68	2.03 (14.3)
Molburg et al. *[4]*	2003	100.5	120.5 tpd H_2	3.3	1.12 (7.88)
Mueller-Langer et al. *[5] (current)*	2007	191.8	298.8 tpd H_2[c]	6.9	1.56 (10.99)
Mueller-Langer et al. *[5] (future)*	2007	181.3	298.8 tpd H_2[c]	8.31	1.83 (12.91)
Ewan et al. *[6]*	2005	72.42	150 tpd H_2	4.54	1.14 (8.00)
Hosseini et al. *[7]*	2016				1.03 (7.25)
Salkuyeh et al. *[8]*	2017	241	446 tpd H_2	2.65	1.07 (7.54)
IEAGHG [9]	2017	212	215.9 tpd H_2	7.44	1.57 (11.08)
Muradov [10]	2000	*	87 tpd H_2	3.25	1.24 (8.70)
Keipi et al. *[11]*	2018	165.9	208.8 tpd H_2	4.47	2.16 (15.19)

* Data not provided in the study
a Based on a HHV of 142 MJ $kg^{-1}H_2$
b Euro to USD exchange rate of $1.24 €$^{-1}$
c Based on 0.083 kgH_2 $m^{-3}H_2$

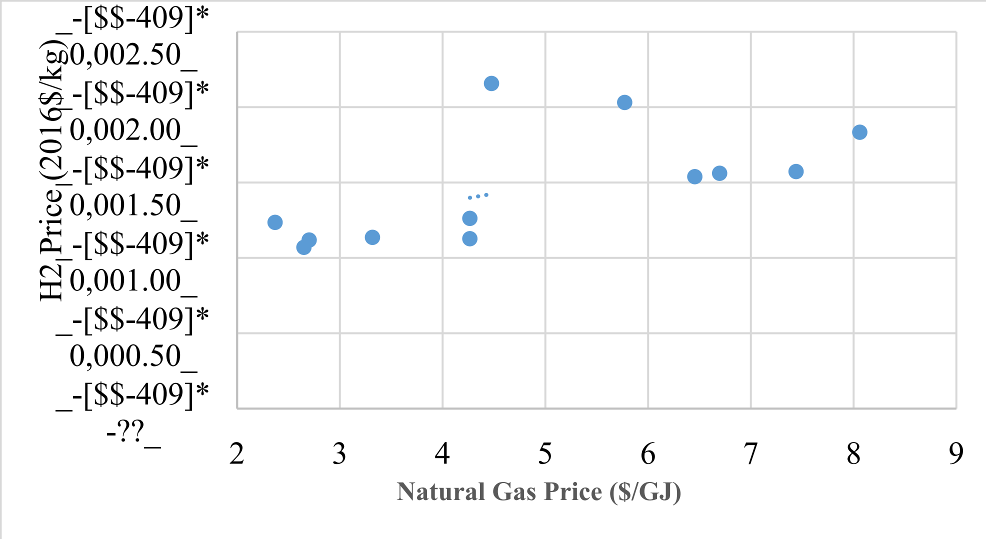

Figure S1: Hydrogen cost (2016 USD $kg^{-1}H_2$) as a function of natural gas price (2016 USD GJ^{-1}) reported in the literature summarized in Table S1.

Table S2:A summary of recent hydrogen production costs via SMR with CCS available in the literature. All costs have been converted to 2016 USD using the CEPCI.

Study	**Year of Study**	**Hydrogen Cost $ $kg^{-1}H_2$ ($ GJ^{-1})[g]**	**Carbon Avoidance Cost ($ $t^{-1}CO_2$)**	**Included T&S Cost ($ $t^{-1}CO_2$)**	**Capture Rate**
National Research Council [1] (current)	2004	1.49 (10.48)	30.13	*	85%
National Research Council [1] (future)	2004	1.24 (8.76)	16.39	*	86%
Molburg et al. *[4]*	2003	1.51 (10.63)	9.432	*	*
Mueller-Langer et al. *[5] (current)*	2007	1.82 (12.78)	32.98	15.34 [a]	70% [b]
Mueller-Langer et al. *[5] (future)*	2007	2.02 (14.19)	23.4	8.95 [a]	70% [b]
Ewan et al. *[6]*	2005	1.82 (12.83)	65.9	6.9 [c]	*
Hosseini et al. *[7]*	2016	1.22 (8.59)	*	*	*
Salkuyeh et al. *[8]*	2017	2.16 (15.21)	136.25	*	90%
IEAGHG [9]	2017	2.28 (16.03)	96.15	12.4	90%
Muradov [10]	2000	1.71 (12.04)	*	*	80%
Keipi et al. *[11]*	2018	2.81 (19.77)	103.92	*	60%
Collodi [12]	2009	*	39.9-46.3	*	60%
Collodi [12]	2009	*	55.3-56.9	*	90%
Bonaquist [13]	2010	*	40-50 [d]	*	50%
Lemus et al. [14]	2010	*	50 [e]	*	50% [d]

Meerman et al. [15]	2012	[f]	48[g]	*	61%

* Not included in the study

a Specifically to cover a transport distance of 100km per pipeline and injection into a saline aquifer

b 85% of syngas stream

c $3.45 $t^{-1}CO_2$ compressed and $3 per 100km of pipeline, no storage included

d Allowance required to trigger investment in 50% capture

e Refers to a carbon tax required for economic capture of 50%

g For production costs within €5-9 GJ^{-1}, CCS increases H_2 production costs by 15-28%

f Uncertainty range of $43-78 $t^{-1}CO_2$ for 61% capture

g Based on a HHV of 142 MJ $kg^{-1}H_2$

Table S3: A summary of recent hydrogen production costs via coal gasification available in the literature. All costs have been converted to 2016 USD using the CEPCI.

Study	**Year of Study**	**Capital Cost million$**	**Plant Size**	**Feedstock Price $ GJ^{-1}**	**Hydrogen Cost $ kg^{-1}H$_2$ ($ GJ^{-1})^a**
National Research Council [1] (current)	2004	1442.6	1,200 tpd H_2	1.42	1.17 (8.24)
National Research Council [1] (future)	2004	1090.5	1,200 tpd H_2	1.42	0.87 (6.10)
Kreutz et al. [16]	2002	1173.5	770.7 tpd H_2	1.73	1.18 (8.29)
Rutkowski [17]	2005	504.3	255.4 tpd H_2	1.33	1.55 (10.92)
Mueller-Langer et al. *[5] (current)*	2007	480	298.8 tpd H_2^{b}	2.6	1.56 (10.99)
Mueller-Langer et al. *[5] (future)*	2007	441.7	298.8 tpd H_2	2.73	1.52 (10.74)
Ewan et al. [6]	2005	286.3	150 tpd H_2	1.43	1.55 (10.92)
Gray and Tomlinson [18]	2002	510.4	309.5	1.33	1.41 (9.99)

a Based on a HHV of 142 MJ.kg-1.H2
b A Euro to USD exchange rate of $1.24 per €

Table S4: A summary of recent hydrogen production costs via coal gasification with CCS available in the literature. All costs have been converted to 2016 USD using the CEPCI

Study	**Year of Study**	**Hydrogen Cost $ $kg^{-1}.H_2$ ($ GJ^{-1}) [a, b]**	**Carbon Avoidance Cost ($ $t^{-1}CO_2$)**	**Included T&S Cost ($ $t^{-1}CO_2$)**	**Capture Rate**
National Research Council [1] (current)	2004	1.45 (10.22)	17.81	12.19	90%
National Research Council [1] (future)	2004	1.32 (9.28)	17.63	12.19	90%
NREL [2]	2009	2.37 (16.70)	*	*	*
Davison et al. [19]	2009	2.25 (15.88)[c]	*	*	85%
Mueller-Langer et al. *[5] (current)*	2007	2.2 (15.47)	25.19	15.34[d]	92%
Mueller-Langer et al. *[5] (future)*	2007	2 (14.06)	18.41	8.95[d]	92%
Mueller-Langer et al. *[5] (advanced coal current)*	2007	1.91 (13.42)	17.26	15.34	92%
Mueller-Langer et al. *[5] (advanced coal future)*	2007	1.58 (11.12)	15.47	8.95	92%
Ewan et al. [6]	2005	3.6 (25.37)	*	*	*
Kreutz et al. [16]	2002	1.40 (9.87)	15.34	6.85	91.7%
NREL [3]	2013	2.12 (14.96)	*	*	*
Gray and Tomlinson [18]	2002	1.70 (11.96)	*	13.9	87%
IEAGHG [20]	2014	2.28 (16.10)	e	11.84	90.1%

a Based on a HHV of 142 MJ $kg^{-1}H_2$
b A Euro to USD exchange rate of $1.24 per €
c Reported CAC is not shown here due to avoided burden allocation across hydrogen and power generation
d Specifically to cover a transport distance of 100km per pipeline and injection into a saline aquifer
e No CAC specified in the study, reasoning given to avoided burden allocation

Table S5: A summary of recent hydrogen production costs via biomass gasification available in the literature. All costs have been converted to 2016 USD using the CEPCI

Study	**Year**	**Capital Cost**	**Plant Size**	**Fuel Cost ($ GJ^{-1} dry) [a]**	**LCOH $ $kg^{-1}H_2$ ($ GJ^{-1}) [b]**
NREL [2]	2009	186.7	155.2 tpd.H_2	4.6	2.28 (16.05)
NREL [2]	2009	178.9	155.2 tpd.H_2	2.6	1.86 (13.12)
Miller et al. [21]	2017	103.7	50 tpd.H_2	4.58	2.31 (16.25)
Yao et al. [22] [c]	2016	12.3	2.16 tpd.H_2	36	7.43 (52.36)
Yao et al. [22] [c]	2016	15	2.16 tpd.H_2	9.6	7.24 (50.98)
IEA [23]	2007	*	*	3.1	3 (21.14)
National Research Council [1] (current)	2013	115.5	24 tpd.H_2	2.7	2.20 (15.47)
National Research Council [1] (future)	2013	56.3	24 tpd.H_2	1.8	1.57 (11.03)
Mueller-Langer et al. *[5] (current)*	2007	536	113.5[C] tpd.H_2	5.5	2.18 (15.34)
Mueller-Langer et al. *[5] (future)*	2007	415.4	113.5[c] tpd.H_2	4.9	1.85 (13.04)
National Research Council [1] (Biomass Gassification + CCS current)	2013	118.3	24 tpd.H_2	2.7	2.27 (16.00) [d]
National Research Council [1] (Biomass Gassification + CCS future)	2013	57.8	24 tpd.H_2	1.8	1.63 (11.50) [d]

a Based on a HHV of 20 MJ kg^{-1} dry biomass, inclusive of planting, fertilization and truck transportation unless otherwise specified
b Based on a HHV of 142 MJ $kg^{-1}H_2$
c Study has been removed from the cost estimate due to very small production volumes
d Specific capture rate of 70%, CAC and transport and storage costs not specified.

Table S6: A summary of recent hydrogen production costs via methane pyrolysis available in the literature. All costs have been converted to 2016 USD using the CEPCI

Study	**Year**	**Capital Cost**	**Plant Size**	**Fuel Cost ($ GJ^{-1})**	**Carbon Value ($ t^{-1})**	**LCOH $ $kg^{-1}H_2$ ($ GJ^{-1}) [a]**
Mondal et al. *[24]*	2010	286.2	196.5	0.7	0	1.96 (13.85)
Keipi et al. *[11]*	2018	5.21	2.16	6.88	0	3.52 (24.79)
Keipi et al. *[11]*	2018	5.21	2.16	6.88	248	2.45 (17.22)
Muradov [10]	2000	27.49	83	3.26	100	1.03 (7.25)
Muradov [10]	2000	27.49	83	3.26	0	1.44 (10.15)
Parkinson et al. [25]	2017	575[b]	547	4	200	1.62 (11.42)
Nikolaidis et al. [26]	1992	*	*	*	*	2.4 (16.93)
Steinberg et al. [27]	1989	*	*	4.61	[c]	1.62 (11.42)
Parkinson et al. [28]	2018	349	274	4	150	1.39 (9.79)
Spath et al. [29]	2000	164.1	152.9	5.11	300	1.46 (10.31)
Spath et al. [29]	2000	164.1	152.9	5.11	100	2.37 (16.71)

a Based on a HHV of 142 MJ $kg^{-1}H_2$
b Capital cost range of $564-592 million USD depending on heat source configuration
c Carbon product credited but no actual figure provided

Table S7: A summary of recent hydrogen production costs via wind, solar and nuclear electrolysis. All hydrogen production costs have been converted to 2016 USD using the CEPCI. Individual item costs have not been escalated and are presented as original costs reported in each individual study.

Study	**Type**	**Year**	**Capital Cost**	**LCOH $ kg^{-1}.H_2 ($ GJ^{-1}) [a]**	**Specified Parameters /Comments**
Bockris et al. [30]	Wind Electrolysis	2007	*	3.61 (25.4)	LCOE $0.045 kWh^{-1}, 100 mA cm^{-2}, alkaline cell
Greiner et al. [31]	Wind Electrolysis	2007	€900 kW^{-1} turbine cost, €1300 kW^{-1} electrolyzer, €5.1mil total cost	7.03 (49.52)	€0.062 kWh^{-1} LCOE, Diesel Generator Backup[a], Electricity usage 42 kWh kg^{-1}H_2, alkaline cell
NREL 2006 [32]	Wind Electrolysis	2006	$700 kW^{-1} electrolyzer	4.16-5.04 (29.3-35.5)	Wind electricity purchased LCOE $0.038 kWh^{-1}, 81% capacity factor
Mueller-Langer et al. [5]	Wind Electrolysis	2007	*€3.3mil* total Capex[b]	9.08 (63.94)	90% load factor, alkaline cell, 64-70% overall efficiency
NREL 2008 [33]	Central Wind Electrolysis	2008	$403.2 kW^{-1} electrolyzer, $2120 kW^{-1} installed turbine cost, $50.1 mil total Capex[c]	2.66-7.73[d] (18.76-51.24)	98% electrolyzer load factor, 106 MW installation, 50 kWh kg^{-1}H_2 requirement
Acar et al. [34]	Wind Electrolysis	2014	*	6.68 (47.01)	*
Nikolaidis et al. [26]	Wind Electrolysis	2005	$500 kW^{-1} electrolyzer	6.98 (49.13)	Capacity factor 65%
NREL 2011 [35]	Central Wind Electrolysis	2011	$403.2 kW^{-1} electrolyzer	4.42 (31.12)	Wind LCOE $0.064 kWh^{-1}, 53.4 kWh kg^{-1}H_2, alkaline cell, 73% cell efficiency
Mason [36]	Wind Electrolysis	2005	$900 kW^{-1} electrolyzer, $7.6billion total Capex	3.56 (25.05)	Wind LCOE $0.049 kWh^{-1}, 34% wind capacity factor, 500 W m^{-2} wind resource
Ewan et al. [6]	Wind	2005	$150mil per 100 MW wind	7.04 (49.54)	Wind LCOE $0.076

	Electrolysis		farm[e]		kWh^{-1}
NREL 2013 [37]	Central Wind Electrolysis	2013	*	4.4 (31)	*
Pregger et al. [38]	Solar Electrolysis	2009	*	10.62 (74.8)	PV LCOE[f] *€0.095 kWh^{-1}, alkaline cell*
NREL 1998 [39]	Solar Electrolysis	1998	\$450 kW^{-1} DC electrolyzer, 750-2000 kW^{-1} PV Panel Cost, 10 MWe installation	8.05-15.16 (56.7-106.7)	Solar capacity factor 28%, electrolyzer efficiency 82%, \$4.96 kW^{-1} panel maintenance
Gray and Tomlinson [18]	Central Solar Electrolysis	2001	\$1200-2400 kW^{-1} peak PV cost, 150 MMSCFD H_2 production	4.44-8.32 (31.25-58.6)	33% capacity factor, 90% plant utilization[g], 18% panel efficiency, 85% electrolyzer efficiency, 275 W m^{-2} resource
Acar et al. [34]	Solar Electrolysis	2014	*	8.8 (62)	*
Nikolaidis et al. [26]	Solar Electrolysis	2007	\$400 kW^{-1} electrolyzer, \$0.75-5 W^{-1} PV panel cost	5.96-23.99 (41.96-168.9)	28% Solar capacity factor
Ewan et al. [6]	Solar Electrolysis	2005	\$60 m^{-2} PV panel cost	17.3 (121.8)	\$0.244 kWh^{-1}, 30-60 yr. panel life, 26 panel capacity factor, 12% PV efficiency, 76% overall electrolyzer efficiency, 98% availability
Mason [36]	Solar Electrolysis	2005	\$917 kW^{-1} PV panel cost	3.34 (23.5)	12% efficient PV panel, 271 W m^{-2} resource
Shaner et al. [40]	Solar Electrolysis	2016	\$371 m^{-2} Panel cost, \$260mil total capex, 10 tpd H_2 production	11.47 (80.75)[h]	PV efficiency 16%, Electrolyzer plant efficiency 61%, Electrolyzer and PV capacity factor 20.4%
Wang et al. [41]	Nuclear High Temperature Electrolysis	2003	173-208 tpd H_2	3.17-6.47 (22.3-45.55)	773-1073 K temperature, 41-52% overall efficiency
Nikolaidis et	Nuclear	2006	\$500 kW^{-1} electrolyzer,	4.15-7.98	54.3 kWh $kg^{-1}H_2$ energy requirement,

al. [26]	Electrolysis		1000 kg day^{-1} H_2	(31.69-56.2)[i]	73% cell efficiency, \$0.048 kWh^{-1} LCOE
Ewan et al. [6]	Nuclear Electrolysis	2005	\$483.6mil total capex, 150 tpd H_2	6.01 (42.33)	\$0.6 kWh^{-1} LCOE, 28% overall system efficiency, 75% cell efficiency
Mueller-Langer et al. [5]	Nuclear Electrolysis	2007	*	3.99 (28.1)	7884 hrs yr^{-1} operating, 64-70% efficiency
Harvego et al. [42]	Nuclear High Temperature Electrolysis	2010	\$200 kW^{-1} electrolyzer cost[j], 600 MW_{th} facility	3.18 (22.37)	47.1% overall system efficiency, operating temperature 900 °C
Hauch et al. [43]	Nuclear High Temperature Electrolysis	2003	€350-550 kW^{-1} electrolyzer cost, total investment cost €6300 m^{-2} cell area	1.48-2.42 (10.43-17.08)	LCOE €0.014-0.037 kWh^{-1}, operating temperature 950 °C, 66% of LCOH from electricity
Parkinson et al. [28]	Nuclear Electrolysis	2016	\$800 kW^{-1} electrolyzer cost, \$829.1mil total capex, 100 kta H_2 production	6.2-7.13[k] (43.7-50.21)	\$0.1 kWh^{-1} LCOE[L], 54.3 kWh kg$^{-1}H_2$

* Not provided in this study
a A €0.028 kWh^{-1} charge for grid electricity backup
b Capital costs of individual electrolyzer or generation technology not provided
c Represents a future scenario where electrolyzer capital cost is reduced from mass production
d Varies with wind class site and grid electricity supply. Electricity supply ranges from \$0.046-
e No electrolyzer cost or scale provided
f Electricity costs in 2020 in North Africa, inclusive of 3000km of HVDC transmission
g Grid electricity top-up
h Un-taxed production value at plant gate
i At 97% capacity factor and electricity supply of \$0.048 kWh^{-1}, using only off-peak electricity the capacity factor is lowered to 47% and LCOH increased to \$7.98 kg$^{-1}H_2$
j One third of SOFC modules replaced annually
k Range of hydrogen values generated from varying uninstalled electrolyzer capital cost from \$400-800 kW^{-1}
l Sensitivity of LCOE from \$0.02-0.1 kWh^{-1} changes H_2 price from \$2.80-7.13 for uninstalled electrolyzer capital cost of \$800 kW^{-1}

Table S8: LCOH of the S-I and Cu-Cl nuclear thermochemical cycles reported in the literature

Study	**Cycle**	**Year of Study**	**Plant Size**	**Hydrogen Cost $ kg^{-1}H$_2$ ($ GJ^{-1})**
Wang et al. [41]	S-I Cycle	2010	200 tpd.H_2	2.05 (14.42)
Acar et al. [34]	S-I Cycle	2014	*	1.79 (12.58)
Dincer et al. [44]	S-I Cycle	2015	*	1.95 (13.7)
Nikolaidis et al. [26]	S-I Cycle	2017	800 tpd.H_2	2.71 (19.09)
Wang et al. [41]	Cu-Cl Cycle	2010	200 tpd.H_2	2.70 (18.98)
Acar et al. [34]	Cu-Cl Cycle	2014	*	1.60 (11.26)
Dincer et al. [44]	Cu-Cl Cycle	2015	*	2.53 (17.8)
Nikolaidis et al. [26]	Cu-Cl Cycle	2017	7 tpd.H_2	(2.35 (16.57)
Ewan et al. [6]	Nuclear Thermochemical Cycle	2005	*	1.47 (10.34)

Table 9: PEM Electrolyzer Stack Design Assumptions

Component	**Value**
Theoretical Minimum Energy (kwh $kg^{-1}H_2$)	39.3
Cell Voltage Efficiency	85%
Total Balance of Plant (kWh $kg^{-1}H_2$)	5.04
Total Electrical Usage (kWh kg^{-1}) [45]	51.26
DI Water Cost ($ ML^{-1}) [45]	477
Electrode Replacement Cost (% of Purchased Equipment Cost) [45]	15% every 7 years
Capital Scaling Factor	1

Table S10: Economic Assumptions used in the discounted cash flow analysis

Fixed Financial Parameter	**Value**
Year of Analysis	2016
Construction Period	2 years
Start-Up Period	6 months
Start-Capacity	50%
Plant Lifetime (electrolyser facility)	25 Years
On-Stream Factor	Technology Dependent
Inflation	2 %
Weighted Average Cost of Capital	10% (Real, After Tax)
Finance	100% Equity
Capital Depreciation	MACRS 7-Year depreciation schedule [45]
Decommissioning Cost	10% of Depreciable Capital
Plant Salvage Value	10% of Depreciable Capital
Company Tax Rate	38.9%

Table S11: Fixed operating cost assumptions used in the electrolyzer discounted cash flow analysis

Fixed Operating Costs	**Value**
Insurance/Local Taxes/Royalties	2% Full Capital
Maintenance	2% Direct Capital
Labour	Calculated based on Parsons Infrastructure Technology Group [46]
Operating Supplies	10% Maintenance
Supervision	25% Labour
Lab/QC/QA	10% Operating Labour

Table S12: Process indirect and direct costs using in the electrolyzer discounted cash flow analysis

CAPEX Costs	**Value**
Equipment Setting [45]	12% PCE
Site Development [45]	2% PCE
Contractor and Engineering Fee	8%
Owner Engineering and Oversight	15%
Contingency	15%
Start-up Costs	5% Full Capital
Working Capital	5% Full Capital

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