Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

CORRECTION

View Article Online
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Cite this: *Energy Environ. Sci.*, 2022, **15**, 5425

DOI: 10.1039/d2ee90059a

rsc.li/ees

Correction: Levelized cost of CO_2 mitigation from hydrogen production routes

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Correction for 'Levelized cost of CO_2 mitigation from hydrogen production routes' by B. Parkinson *et al.*, *Energy Environ. Sci.*, 2019, **12**, 19–40, https://doi.org/10.1039/C8EE02079E.

Some of the references had missing or incorrect details; corrected sections of the affected text are provided below. The reference list has also been corrected and is reproduced in full at the end of this correction.

In Section 3.1, "For literature studies including natural gas supply chain contributions to GHG emissions, the reported total range of LCE values are 10.72–15.86 kg CO_2e kg^{-1} H_2 (average of 12.4 of kg CO_2e kg^{-1} H_2)[26–34] without CCS and 3.1–5.9 kg CO_2e kg^{-1} H_2 (average of 4.3 kg CO_2e kg^{-1} H_2) with CCS at 90% capture.[27,28,32,33,35]" should read as "For literature studies including natural gas supply chain contributions to GHG emissions, the reported total range of LCE values are 10.72–15.86 kg CO_2e kg^{-1} H_2 (average of 12.4 of kg CO_2e kg^{-1} H_2)[30–38] without CCS and 3.1–5.9 kg CO_2e kg^{-1} H_2 (average of 4.3 kg CO_2e kg^{-1} H_2) with CCS at 90% capture.[31,32,36,37,39]"

"Direct GHG emissions from the SMR hydrogen production phase are approximately 8–10 t CO_2e t^{-1} H_2, 60% of which is generated from the process chemistry, while the remaining 40% arises from heat and power sources required.[36]" should read as "Direct GHG emissions from the SMR hydrogen production phase are approximately 8–10 t CO_2e t^{-1} H_2, 60% of which is generated from the process chemistry, while the remaining 40% arises from heat and power sources required.[26]"

"The majority of CO_2 produced exits in two streams, a diluted stream (stack gases with CO_2 concentration 5–10 vol%) and a concentrated stream (approximately 50% by vol after pressure swing adsorption).[37]" should read as "The majority of CO_2 produced exits in two streams, a diluted stream (stack gases with CO_2 concentration 5–10 vol%) and a concentrated stream (approximately 50% by vol after pressure swing adsorption).[27]"

"If deep decarbonisation is required and emissions must be further reduced from the entire process, then an amine solvent (MEA) based CCS process might be used to capture up to 90% of the CO_2 contained in the stack gases,[38] although demonstrated removal rates are typically 80%.[39]" should read as "If deep decarbonisation is required and emissions must be further reduced from the entire process, then an amine solvent (MEA) based CCS process might be used to capture up to 90% of the CO_2 contained in the stack gases,[28] although demonstrated removal rates are typically 80%.[29]"

In Section 3.1.2, "In contrast, the post-demonstration of CCS in the EU reports by the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) detail the costs of CO_2 transport *via* pipeline (higher for shipping) to range from \$2.4–13 t^{-1} CO_2,[99] and storage and monitoring from \$8–23 t^{-1} CO_2,[73] depending on the storage site location and degree of characterization." should read as "In contrast, the post-demonstration of CCS in the EU reports by the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) detail the costs of CO_2 transport *via* pipeline (higher for shipping) to range from \$2.4–13 t^{-1} CO_2,[73] and storage and monitoring from \$8–23 t^{-1} CO_2,[73] depending on the storage site location and degree of characterization."

In Section 3.2, "The lower C : H ratio in coal relative to natural gas results in significantly higher direct CO_2e emissions from the process (14.4–25.31 kg CO_2e kg^{-1} H_2), with an average value of 19.14 kg CO_2e kg^{-1} H_2.[8,22,28,43–45]" should read as "The lower C : H ratio in coal relative to natural gas results in significantly higher direct CO_2e emissions from the process (14.4–25.31 kg CO_2e kg^{-1} H_2), with an average value of 19.14 kg CO_2e kg^{-1} H_2.[8,22,32,43–45]"

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In Section 3.2.1, "This represents a relatively small portion of the average 0.45 kg CO_2e kg^{-1} H_2 (range 0.32–0.77 kg CO_2e kg^{-1} H_2) for coal extraction, processing and transportation reported in the literature for subbituminous coal supply chains.[27,30,45] The range of LCE from coal gasification with CCS ($\geq$90% capture) presented in the literature range from 0.77–5.2 kg CO_2e kg^{-1} H_2[27,30,44–46] with an average of 4.56 kg CO_2e kg^{-1} H_2." should read as "This represents a relatively small portion of the average 0.45 kg CO_2e kg^{-1} H_2 (range 0.32–0.77 kg CO_2e kg^{-1} H_2) for coal extraction, processing and transportation reported in the literature for subbituminous coal supply chains.[31,34,45] The range of LCE from coal gasification with CCS ($\geq$90% capture) presented in the literature range from 0.77–5.2 kg CO_2e kg^{-1} H_2[31,34,44,45,48] with an average of 4.56 kg CO_2e kg^{-1} H_2."

In Section 3.2.2, "Whilst several studies for coal gasification integrated with CCS for power generation are available,[47,48]" should read as "Whilst several studies for coal gasification integrated with CCS for power generation are available,[46,47]".

"CAC reference plant for IGCC facilities for power production is a supercritical pulverized coal (SCPC) plant without capture (not a similar IGCC plant without capture), which would be the lower cost route for coal-fired power plants without capture.[45] This results in an increase in the average CAC from \$43.92 t^{-1} CO_2 (for IGCC with CCS to IGCC without) to \$77.34 t^{-1} CO_2 (excluding transport and storage for both) as reported in a recent review by Rubin *et al.*[45] An average value of \$43.92 t^{-1} CO_2 for IGCC compared to a SMR baseline has been used.[45]" should read as "CAC reference plant for IGCC facilities for power production is a supercritical pulverized coal (SCPC) plant without capture (not a similar IGCC plant without capture), which would be the lower cost route for coal-fired power plants without capture.[46] This results in an increase in the average CAC from \$43.92 t^{-1} CO_2 (for IGCC with CCS to IGCC without) to \$77.34 t^{-1} CO_2 (excluding transport and storage for both) as reported in a recent review by Rubin *et al.*[46] An average value of \$43.92 t^{-1} CO_2 for IGCC compared to a SMR baseline has been used.[46]"

In Section 3.4, "For a conservative approach in this study, a LCOH of \$1.76 kg^{-1} H_2 is estimated based on a recent model developed by Parkinson *et al.*,[71]" should read as "For a conservative approach in this study, a LCOH of \$1.76 kg^{-1} H_2 is estimated based on a recent model developed by Parkinson *et al.*,[70]".

"Several studies[35,68–70] report the direct emissions of a pyrolysis facility to range from 0.2–2.5 kg CO_2 kg^{-1} H_2." should read as "Several studies[39,68–70] report the direct emissions of a pyrolysis facility to range from 0.2–2.5 kg CO_2 kg^{-1} H_2."

"For methane pyrolysis using the updated supply chain emissions discussed in Section 3.1, this study estimates the supply chain emissions contribute 4.28 kg CO_2e kg^{-1} H_2 for the median case, with a range of 3.26–6.44 kg CO_2e kg^{-1} H_2 using an overall process efficiency of 53% HHV.[71]" should read as "For methane pyrolysis using the updated supply chain emissions discussed in Section 3.1, this study estimates the supply chain emissions contribute 4.28 kg CO_2e kg^{-1} H_2 for the median case, with a range of 3.26–6.44 kg CO_2e kg^{-1} H_2 using an overall process efficiency of 53% HHV.[70]"

In Section 3.5, "SOEC are the most electrically efficient of the three technologies, but are currently in the R&D stage facing challenges with corrosion, seals, thermal cycling and chromium migration.[73] PEM electrolysis is currently more expensive than alkaline technologies, but is an attractive future technology due to higher current densities ($>$2 A cm^{-2}), higher efficiencies (the largest cost driver), dynamic operation and compact system design.[74] An excellent summary of the technical specifications of each technology has been compiled by Bhandari *et al.*[28]" should read as "SOEC are the most electrically efficient of the three technologies, but are currently in the R&D stage facing challenges with corrosion, seals, thermal cycling and chromium migration.[52] PEM electrolysis is currently more expensive than alkaline technologies, but is an attractive future technology due to higher current densities ($>$2 A cm^{-2}), higher efficiencies (the largest cost driver), dynamic operation and compact system design.[74] An excellent summary of the technical specifications of each technology has been compiled by Bhandari *et al.*[32]"

In Section 3.5.1, "The direct emissions from electrolytic hydrogen production are very low, but the indirect emissions associated with electricity feedstock and electrolyzer systems must be considered.[28]" should read as "The direct emissions from electrolytic hydrogen production are very low, but the indirect emissions associated with electricity feedstock and electrolyzer systems must be considered.[32]"

"Little data is available on the LCE contribution from electrolyser manufacturing and replacements, with estimates suggesting a relatively small contribution in the range of 30–50 g CO_2e kg^{-1} H_2[28,76,77]" should read as "Little data is available on the LCE contribution from electrolyser manufacturing and replacements, with estimates suggesting a relatively small contribution in the range of 30–50 g CO_2e kg^{-1} H_2[32,76,77]".

In Section 3.5.2, "PEM was chosen as the reference electrolyser technology operating with an 85% cell voltage efficiency ($\sim$51 kW h kg^{-1} H_2).[106]" should read as "PEM was chosen as the reference electrolyser technology operating with an 85% cell voltage efficiency ($\sim$51 kW h kg^{-1} H_2).[75]"

In Section 4.3, "These decarbonization fractions are not commensurate with the decarbonization targets required in transport, heat and industry under many scenarios, particularly as global aspirations turn to net zero emissions in the second half of the 21st century.[84] This highlights that technologies such as carbon capture and sequestration may potentially be an expensive exercise in heroic futility if all aspects of hydrogen supply chains are not addressed. No cost is currently applied to methane emissions and the costs of mitigating supply chain emissions are less well understood than emissions at the point of conversion. It has been suggested that 75% of global methane emissions from oil and gas supply chains are mitigatable, with half of these achieved at a positive net present value.[85]" should read as "These decarbonization fractions are not commensurate with the decarbonization targets required in transport, heat and industry under many scenarios, particularly as global aspirations turn to net zero emissions

in the second half of the 21st century.[126] This highlights that technologies such as carbon capture and sequestration may potentially be an expensive exercise in heroic futility if all aspects of hydrogen supply chains are not addressed. No cost is currently applied to methane emissions and the costs of mitigating supply chain emissions are less well understood than emissions at the point of conversion. It has been suggested that 75% of global methane emissions from oil and gas supply chains are mitigatable, with half of these achieved at a positive net present value.[86]''

''With enough incentive (*e.g. via* pollution tax as per ref. 86)'' should read as ''With enough incentive (*e.g. via* pollution tax as per ref. 127)''.

In Section 4.3.1, ''The deployment of CCS at-scale is the only method widely considered to be available to substantially mitigate CO_2 emissions from fossil fuels, which so far has failed to meet ambitious expectations, and continued delays of demonstration projects are causing considerable uncertainty about the role CCS will play in carbon mitigation.[87] This study has shown that equipping CCS to SMR (90% capture) only effectively reduces the life cycle GHG footprint of hydrogen production by 38–76%, depending on the contribution of supply chain emissions. Additionally, the capture rates may currently be lower than 90%.[39]'' should read as ''The deployment of CCS at-scale is the only method widely considered to be available to substantially mitigate CO_2 emissions from fossil fuels, which so far has failed to meet ambitious expectations, and continued delays of demonstration projects are causing considerable uncertainty about the role CCS will play in carbon mitigation.[112] This study has shown that equipping CCS to SMR (90% capture) only effectively reduces the life cycle GHG footprint of hydrogen production by 38–76%, depending on the contribution of supply chain emissions. Additionally, the capture rates may currently be lower than 90%.[29]''

''The operational and capital costs would also change with different capture rates, with higher capture rates requiring greater fuel duty and equipment.[88]'' should read as ''The operational and capital costs would also change with different capture rates, with higher capture rates requiring greater fuel duty and equipment.[113]''

''A detailed review of carbon capture and utilization options is presented by Hunt *et al.*[89]'' should read as ''A detailed review of carbon capture and utilization options is presented by Hunt *et al.*[114]''

''Amine-based CO_2 absorption systems are also commercially mature technologies in the chemicals sector.[90]'' should read as ''Amine-based CO_2 absorption systems are also commercially mature technologies in the chemicals sector.[115]''

''Several proposals for equipping CCS to industrially active clusters with shared transport and storage infrastructure have been proposed and it is widely agreed the largest cost reductions can be achieved here.[91–95]'' should read as ''Several proposals for equipping CCS to industrially active clusters with shared transport and storage infrastructure have been proposed and it is widely agreed the largest cost reductions can be achieved here.[116–120]''

''Long term monitoring of storage sites is also required to ensure leakage rates to the atmosphere of less 0.1% $year^{-1}$ needed to ensure effective climate change abatement are maintained.[96,97] Commercial scale storage sites will also have to manage the risks of financial penalties for unforeseen leakages.[98]'' should read as ''Long term monitoring of storage sites is also required to ensure leakage rates to the atmosphere of less 0.1% $year^{-1}$ needed to ensure effective climate change abatement are maintained.[121,122] Commercial scale storage sites will also have to manage the risks of financial penalties for unforeseen leakages.[123]''

In Section 4.3.2, ''It should be noted however, there is a large body of literature that suggests up to 60% of coal mine methane mitigation is achievable at relatively low cost.[99,100]'' should read as ''It should be noted however, there is a large body of literature that suggests up to 60% of coal mine methane mitigation is achievable at relatively low cost.[128,129]''

''Coal-to-hydrogen processes are however less prevalent as dedicated hydrogen producers, with advanced coal gasification concepts aiming to integrate CO_2 separation with water–gas shift reactions to achieve higher process efficiencies with ease of CO_2 capture.[101]'' should read as ''Coal-to-hydrogen processes are however less prevalent as dedicated hydrogen producers, with advanced coal gasification concepts aiming to integrate CO_2 separation with water–gas shift reactions to achieve higher process efficiencies with ease of CO_2 capture.[130]''

''The order of magnitude estimates for coal-to-hydrogen with CCS are likely to remain around the \$60–100 t^{-1} CO_2.[47]'' should read as ''The order of magnitude estimates for coal-to-hydrogen with CCS are likely to remain around the \$60–100 t^{-1} CO_2.[46]''

In Section 4.3.3, ''This finding is of particular importance as the technology is regularly cited in academic literature as a means of producing CO_2-free hydrogen,[2,4,6,9,14,19,21,66,68–70,102–106] which is only achievable if supply chain emissions are low. It should be noted, however, in contrast to technologies such as CCS the storage of a solid by-product carbon is relatively simple either temporarily or permanently, an idea first proposed as the 'carbon moratorium' by Kreysa.[104]'' should read as ''This finding is of particular importance as the technology is regularly cited in academic literature as a means of producing CO_2-free hydrogen,[2,4,6,9,14,19,21,66,68–70,103,104,124,125,131,132] which is only achievable if supply chain emissions are low. It should be noted, however, in contrast to technologies such as CCS the storage of a solid by-product carbon is relatively simple either temporarily or permanently, an idea first proposed as the 'carbon moratorium' by Kreysa.[125]''

''There are several technical challenges associated with management of the solid carbon produced which fouls (cokes) solid catalysts.[102,107–109] However, proponents of the technology claim these limitations can be overcome with appropriate process and reactor design to allow easy separation of the carbon product.[10,52,106,110]'' should read as ''There are several technical challenges associated with management of the solid carbon produced which fouls (cokes) solid catalysts.[131,133–135] However, proponents of the technology claim these limitations can be overcome with appropriate process and reactor design to allow easy separation of the carbon product.[10,52,132,136]''

In Section 4.4, ''It is interesting to note that electrolysis avoidance costs in their current status are comparable to negative emissions technologies such as direct capture, estimated to be \$600–700 t^{-1} CO_2 avoided.[111,112]'' should read as ''It is interesting to note that electrolysis avoidance costs in their current status are comparable to negative emissions technologies such as direct capture, estimated to be \$600–700 t^{-1} CO_2 avoided.[137,138]''

''For example, wind capacity factors have increased markedly in the past decade and in some sites (*e.g.* Denmark) may exceed 50%.[113]'' should read as ''For example, wind capacity factors have increased markedly in the past decade and in some sites (*e.g.* Denmark) may exceed 50%.[139]''

''This is illustrated in Fig. 10(b), which shows the effect of increasing the utilization of an optimistic 50% capacity factor future wind electrolysis scenario using the average EU (~0.275 kg CO_2 kW h^{-1}, \$0.081 kW h^{-1} [114,115]) and French (~0.050 kg CO_2 kW h^{-1}, \$0.0596 kW h^{-1} [114,115]) electricity grids.'' should read as ''This is illustrated in Fig. 10(b), which shows the effect of increasing the utilization of an optimistic 50% capacity factor future wind electrolysis scenario using the average EU (~0.275 kg CO_2 kW h^{-1}, \$0.081 kW h^{-1} [140,141]) and French (~0.050 kg CO_2 kW h^{-1}, \$0.0596 kW h^{-1} [140,141]) electricity grids.''

''Wind and solar power have witnessed substantial cost reductions over the past two decades and potential areas of future cost reduction have been identified by others.[116] The ability of solar PV to meet the required cost reductions to be a more cost competitive mitigation option requires a balance between the investments required to produce and install a module, the total energy provided by that module and its lifetime and conversion efficiency.[117] New materials realising sufficient efficiency, stability and cost will be required.[118]'' should read as ''Wind and solar power have witnessed substantial cost reductions over the past two decades and potential areas of future cost reduction have been identified by others.[142] The ability of solar PV to meet the required cost reductions to be a more cost competitive mitigation option requires a balance between the investments required to produce and install a module, the total energy provided by that module and its lifetime and conversion efficiency.[143] New materials realising sufficient efficiency, stability and cost will be required.[111]''

''Continuous increases in the average capacity of turbines, hub-heights and swept areas have allowed higher utilization factors and reduced costs.[119]'' should read as ''Continuous increases in the average capacity of turbines, hub-heights and swept areas have allowed higher utilization factors and reduced costs.[144]''

''Thermal efficiencies of nuclear and combustion power plants to electricity operating through Rankine cycles range from 31% for a Magnox type to around 40% for an advanced gas cooled reactor.[120]'' should read as ''Thermal efficiencies of nuclear and combustion power plants to electricity operating through Rankine cycles range from 31% for a Magnox type to around 40% for an advanced gas cooled reactor.[145]''

In Section 4.5, ''Although the thermochemical cycle efficiencies (~50%) have yet to be demonstrated at scale, it has been the subject of significant research by the Japan Atomic Energy Agency,[121] General Atomics[122] and Westinghouse.[123]'' should read as ''Although the thermochemical cycle efficiencies (~50%) have yet to be demonstrated at scale, it has been the subject of significant research by the Japan Atomic Energy Agency,[146] General Atomics[147] and Westinghouse.[148]''

''Although unit costs for technologies usually decrease with increasing volume of production, nuclear power has consistently seen the opposite within the United States; which reflects the idiosyncrasies of the regulatory environment as public opposition grew and regulations were tightened.[124] Lovering *et al.*[125]'' should read as ''Although unit costs for technologies usually decrease with increasing volume of production, nuclear power has consistently seen the opposite within the United States; which reflects the idiosyncrasies of the regulatory environment as public opposition grew and regulations were tightened.[149] Lovering *et al.*[150]''

''They concluded that there is no inherent cost escalation trend associated with nuclear technology, and the large variance witnessed in cost trends over time and across different countries, even with similar nuclear reactor technologies, suggests that cost drivers other than learning-by-doing have dominated the cost experience of nuclear power construction.[125] Additionally, as the majority of literature on nuclear power costs have focussed almost exclusively on the United States and France, there is an incomplete picture of the economic evolution of the technology.[125]'' should read as ''They concluded that there is no inherent cost escalation trend associated with nuclear technology, and the large variance witnessed in cost trends over time and across different countries, even with similar nuclear reactor technologies, suggests that cost drivers other than learning-by-doing have dominated the cost experience of nuclear power construction.[150] Additionally, as the majority of literature on nuclear power costs have focussed almost exclusively on the United States and France, there is an incomplete picture of the economic evolution of the technology.[150]''

In Section 4.6, ''Only a very small percentage of solar energy is converted to hydrogen (~6–12 wt% H_2 kg^{-1} biomass[126])'' should read as ''Only a very small percentage of solar energy is converted to hydrogen (~6–12 wt% H_2 kg^{-1} biomass[151])''.

''A recent report[127] suggests with anticipated improvements in agricultural practices and plant breeding, feedstocks may exceed 244 million dry tons at a farm-gate price of \$60 dry ton^{-1}. It has also been proposed that waste biomass feedstocks could be co-fired in coal gasification facilities to further reduce the net CO_2 closer to zero with minimal impact on the downstream flue gas treatment unit.[128] In a plant with post-combustion capture this increases the cost of electricity by 6% and has no impact on the cost of CO_2 avoidance, but the cost depends strongly on the cost of biomass.[128]'' should read as ''A recent report[81] suggests with anticipated improvements in agricultural practices and plant breeding, feedstocks may exceed 244 million dry tons at a farm-gate price of \$60 dry ton^{-1}. It has also been proposed that waste biomass feedstocks could be co-fired in coal gasification facilities to

further reduce the net CO_2 closer to zero with minimal impact on the downstream flue gas treatment unit.[100] In a plant with post-combustion capture this increases the cost of electricity by 6% and has no impact on the cost of CO_2 avoidance, but the cost depends strongly on the cost of biomass.[100]''

''The production of hydrogen from biomass with CCS is one of only a few technologies that may deliver negative emissions at relatively modest costs, which may become important for global decarbonization issues in the second half of this century.[129]'' should read as ''The production of hydrogen from biomass with CCS is one of only a few technologies that may deliver negative emissions at relatively modest costs, which may become important for global decarbonization issues in the second half of this century.[99]''

''This is reflected by several commercial examples of biomass for heat and power[130] but no completed industrial-scale demonstrations of any biomass technology for hydrogen production.[126]'' should read as ''This is reflected by several commercial examples of biomass for heat and power[106] but no completed industrial-scale demonstrations of any biomass technology for hydrogen production.[151]''

In Section 5, ''These decarbonization fractions are not commensurate with the decarbonization targets required in transport, heat and industry under many scenarios, particularly as global aspirations turn to net zero emissions in the second half of the 21st century in line with the Paris Agreement.[84]'' should read as ''These decarbonization fractions are not commensurate with the decarbonization targets required in transport, heat and industry under many scenarios, particularly as global aspirations turn to net zero emissions in the second half of the 21st century in line with the Paris Agreement.[126]''

''This finding is of particular importance as the technology is regularly cited in academic literature as a means of producing CO_2-free hydrogen,[2,4,6,9,14,19,21,66,68–70,102–106]'' should read as ''This finding is of particular importance as the technology is regularly cited in academic literature as a means of producing CO_2-free hydrogen,[2,4,6,9,14,19,21,66,68–70,103,104,125,131,132]''.

The Royal Society of Chemistry apologises for these errors and any consequent inconvenience to authors and readers.

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