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Research Article

Carbon footprinting of carbon capture and -utilization technologies: discussion of the analysis of Carbon XPRIZE competition team finalists

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Abstract

Life cycle assessments (LCAs) of early-stage technologies can provide valuable insights about key drivers of emissions and aid in prioritizing research into further emissions-reduction opportunities. Despite this potential value, further development of LCA methods is required to handle the increased uncertainty, data gaps, and confidentially of early-stage data. This study presents a discussion of the life cycle carbon footprinting of technologies competing in the final round of the NRG COSIA Carbon XPRIZE competition—a US$20 million competition for teams to demonstrate the conversion of CO_2 into valuable products at the scale of a small industrial pilot using consistent deployment conditions, boundaries, and methodological assumptions. This competition allowed the exploration of how LCA can be used and further improved when assessing disparate and early-stage technologies. Carbon intensity estimates are presented for two conversion pathways: (i) CO_2 mineralization and (ii) catalytic conversion (including thermochemical, electrochemical, photocatalytic and hybrid process) of CO_2, aggregated across teams to highlight the range of emissions intensities demonstrated at the pilot for individual life cycle stages. A future scenario is also presented, demonstrating the incremental technology and deployment conditions that would enable a team to become carbon-avoiding relative to an incumbent process (i.e. reducing emissions relative to a reference pathway producing a comparable product). By considering the assessment process across a diverse set of teams, conversion pathways and products, the study presents generalized insights about opportunities and challenges facing carbon capture and -utilization technologies in their next phases of deployment from a life cycle perspective.

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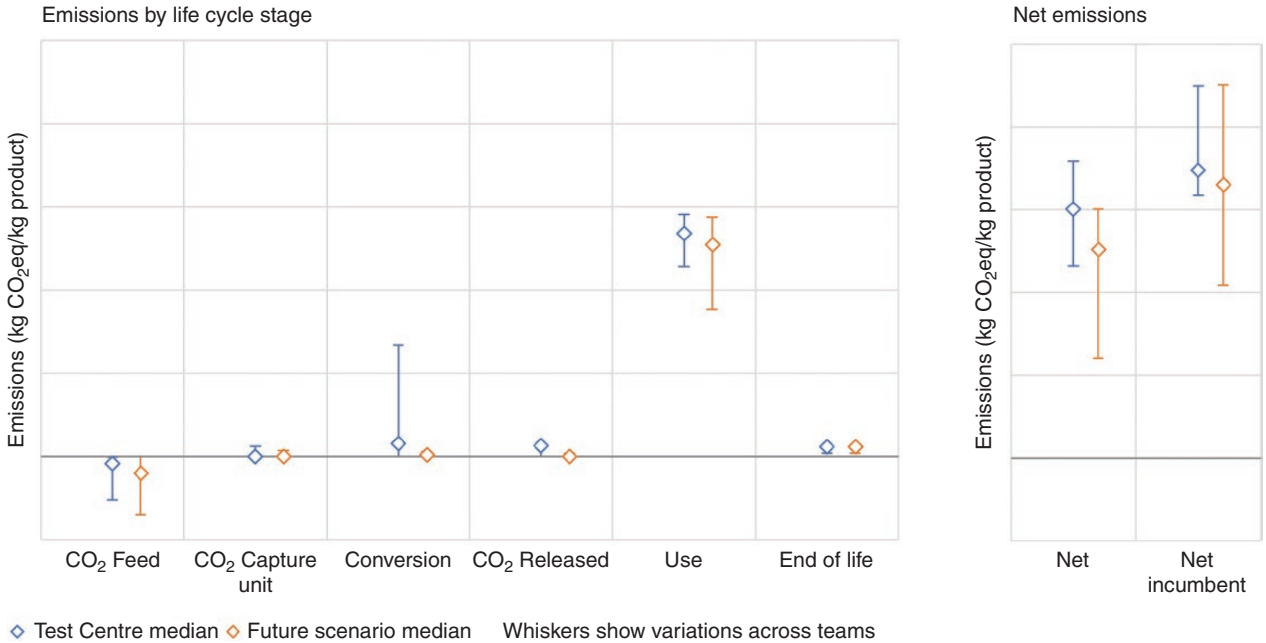
Graphical Abstract



Keywords: CCUS; life cycle assessment; carbon footprinting; carbon capture and utilization

Introduction

Carbon capture and -utilization (CCU) technologies involve the conversion of CO_2 into usable products, such as chemicals, fuels, polymers or building materials, and are gaining global attention. Currently, there is no consensus among scientists regarding the potential role of CCU in climate projections. While some scientists (e.g. [1, 2]) anticipate a minor role in achieving global climate targets, others (e.g. [3, 4]) expect a much larger role as an emissions-mitigation technology. CCU technologies provide two possible pathways for reducing greenhouse gas (GHG) emissions: (i) by providing an opportunity to permanently store CO_2 (for some products) and (ii) by displacing incumbent technologies and products in the market. Further, carbon-conversion products may provide an opportunity to decarbonize industries where electrification and a renewables-based grid alone may be insufficient to meet more ambitious climate targets. One projection from 2016 estimated that CCU technologies could be a US$800 billion market by 2030, utilizing up to 7 billion metric tonnes of CO_2 annually [3].

Life cycle assessment (LCA) takes a systems perspective to evaluate the environmental impacts of a product or service from resource extraction to end of life, or cradle to grave. LCA of emerging technologies such as CCU technologies can face challenges including data availability, uncertainty about technology performance (particularly for early-stage technologies), uncertainty about the market or context in which the technology will be deployed and uncertainty about the product that will be displaced in the market and resulting impacts (e.g. rebound effects) [5]. Increasingly, LCA is being applied to evaluate the GHG-mitigation potential of different CCU technologies, including the application of CCU technologies to produce chemicals [4, 6, 7], transportation fuels [8–13], power-to-X systems [14] and building materials [15, 16]. The projected magnitude of the role that CCU technologies could play in GHG mitigation from a life cycle perspective has varied, from estimates at the scale of gigatons of CO_2eq-annually within individual industries such as chemicals or building materials (e.g. [4, 15]) to minimal climate benefit (e.g. [1]). Findings in the literature generally indicate that CCU technologies require lower-carbon energy (electricity and heat) as well as feedstocks (e.g. hydrogen) to reduce GHG emissions relative to fossil-based incumbent pathways [6, 17]. The magnitude of GHG emissions reductions depends on several factors including: the LCA modelling framework and assumptions [10], technology performance [18], CO_2 source [19], impacts of the temporal storage of CO_2 and sources of electricity, hydrogen and other co-feeds [6, 17], conversion pathway studied [2] and the incumbent or reference pathway selected for comparison [2]. Others (e.g. [2, 17]) have investigated whether CCU technologies are the best use of renewable electricity. Their findings, while not conclusive for all regions and deployment conditions, suggest that the renewable electricity required for CCU technologies would be more effective in mitigating GHG emissions if employed to displace fossil-based electricity production, which remains a substantial portion of electricity generation in many current (as of 2021) electricity grids.

CCU technologies are nascent technologies with many conversion pathways, products, CO_2 sources and end uses at various stages of commercialization or technology-readiness levels [20]. As a result, the performance of these

technologies at the commercial scale is uncertain and technological performance data are relatively limited, representing a challenge for LCA practitioners. Most existing LCA studies derive their technological performance data from thermodynamic relationships (e.g. [4, 18]), chemical-process modelling (e.g. [10, 12]), laboratory data (e.g. [15]) or blended literature data (e.g. [16, 17]). Studies also tend to focus on a subset of products (e.g. chemicals, fuels, polymers or building materials) or a single conversion pathway (e.g. mineralization, catalytic conversion). This limits the types of directional insights that could otherwise be derived by assessing a range of pathways and products to identify the opportunities for CCU technologies to provide the greatest emissions reductions.

This study presents the life cycle carbon footprinting of the team finalists of the Carbon XPRIZE—a US$20 million competition for teams to demonstrate the conversion of CO_2 into valuable products at one of two demonstration facilities (henceforth, 'Test Centres'), located at a coal-fired power plant and a natural gas combined-cycle power plant in Gillette, Wyoming, and Calgary, Alberta, respectively (see https://www.xprize.org/prizes/carbon). The competition was launched in 2015 and nine finalist teams deployed their technologies at demonstration facilities over an up to 30-day operating period ending in November 2020. Two teams were unable to demonstrate their processes at the Test Centres due to COVID-19 but demonstrated their technologies under comparable operating conditions over the same operating period as teams located at the Test Centres.

A panel of eight judges selected the two winning teams, announced in April 2021, one for each demonstration centre or competition track (Alberta and Wyoming) [21]. Teams were judged on several factors including the amount of CO_2 converted and the economic value of the carbon-based products produced [21]. To be eligible for the final award, teams needed to demonstrate that their process could be carbon-avoiding (i.e. having lower GHG emissions) relative to an incumbent process or provide a set of reasonable technology and deployment conditions under which their process *could* become carbon-avoiding relative to an incumbent in a hypothetical future scenario. The hypothetical deployment scenario is intended to show how current (outside of the competition) or near-term deployments could be carbon-avoiding rather than a projection of the maximum emissions reductions achievable by these technologies relative to an incumbent. Our third-party LCA team was recruited to conduct the carbon-footprinting assessment of each technology as they operated at the Test Centre.

To the authors' knowledge, this is the first life cycle study to present the performance of a range of CCU technologies at the scale of a small industrial pilot using consistent deployment conditions, boundaries and methodological assumptions. The study demonstrates advances in developing and deploying CCU technologies that in turn improve LCA estimates using demonstration-facility deployment data to replace theoretical estimates from previous LCAs. The study presents aggregated carbon-intensity estimates to highlight the range of emissions intensities demonstrated at the Test Centre and the incremental technology and deployment conditions that would enable a team to become carbon-avoiding relative to an incumbent process as projected by the teams. By comparing a diverse set of teams, conversion pathways and products, generalized insights can be derived about the types of opportunities and challenges facing CCU technologies in their next phases of deployment. Finally, the study describes the methodological challenges and opportunities of LCA of early-stage technologies and motivates future work on the LCA of CCU technologies.

1 Methods

The goal of the study is to evaluate the carbon footprint of competition team finalists as they performed at the Test Centres during the final round of the XPRIZE competition as well as the set of off-site (e.g. carbon intensity of the electricity source) or future (e.g. location) conditions required to be carbon-avoiding relative to an incumbent technology. Emissions estimates across all teams are presented for the functional unit of 1 kg of product. Emissions are presented using a cradle-to-grave boundary, i.e. including the full life cycle from the source of CO_2 to the end of life of the product produced by that company. To estimate the relative emissions reductions, an incumbent is defined for each team and product by identifying the current largest production method for producing the incumbent in the Alberta or Wyoming market as of 2020 or a similar proxy if those data are unavailable. The Test Centre performance data employed in this study represents a small snapshot in time and is not intended to reflect how the technology would perform at other deployments today or in the future. As such, each competition team also proposed a future deployment scenario, reflecting how they expect their technology to perform at other deployments either today (2020) or in the near term (by 2030). The future scenario is intended to indicate the types of deployment conditions that would enable a team to be carbon-avoiding relative to an incumbent. The future scenario is not intended to be a projection of the future performance of a conversion technology nor an indication of the potential for any technology or technology pathway as a climate solution. More detailed modelling of the future performance of a technology and ideal deployment conditions should be considered in future work but is outside of the scope of the current analysis. For the future scenario, the carbon-avoiding comparison is completed against a future incumbent, accounting for potential changes to the incumbent by 2030 and assumptions about the deployment context for the CCU technology.

Carbon footprinting estimates are aggregated and presented for two types of pathways: (i) mineralization and (ii) catalytic conversion. These two pathways were chosen

due to differences in the potential end uses of products from mineralized CO_2 (typically used in building materials) and catalytic conversion (typically polymers, chemicals or fuels). Mineralization teams are producing the following products: ready-mixed concrete with CO_2 mineralized in wash water from cement trucks, concrete masonry units and nanomaterials for use in concrete. Incumbent selection for mineralization products was based on concrete that would provide a similar service (e.g. concrete masonry unit or concrete with similar strength properties). Catalytic conversion in this study includes thermochemical, photocatalytic, electrocatalytic processes and some hybrid approaches. Catalytic conversion teams are producing ethylene for high-density polyethylene (HDPE) production, syngas for fuel production, fuel- or beverage-grade ethanol and methanol for use as a fuel or in the chemicals industry.

1.1 Carbon-footprinting framework

Cradle-to-grave emissions are estimated, including capture, conversion, separation and downstream processing, to produce a final (end-use) product. Emissions are presented per kg of final product.

A credit is assigned to teams for all CO_2 fed into their process (i.e. substitution is applied, as described in [22]). Note that there are other methods that can be used to handle the multi-product system issues that arise when a facility producing one product also captures and uses the generated CO_2 from their system [23]. The CO_2 is derived from combustion at a natural gas or coal-fired power plant and then captured using post-combustion capture. All capture unit emissions are assigned to the CO_2-derived product. Unconverted CO_2 that is not recycled through the conversion process is assigned as an emission to the CO_2-derived product; however, as these emissions are included in both the CO_2 feed and the CO_2 vented, it does not affect the net emissions from the process using this accounting method. It is assumed that these emissions would have ended up in the atmosphere in the absence of the conversion process. For example, if 90% of the captured CO_2 is converted into a final product, a pathway will have a CO_2 feed of 1.1 kg CO_2eq/kg CO_2 converted and CO_2 vented emissions of 0.1 kg CO_2eq/kg CO_2 converted.

In terms of the end of life of the CO_2-derived product, the carbon in the final product is only assumed to be permanently sequestered for mineralization teams [23]. For teams producing a final product that could be considered temporary (e.g. plastic products that will ultimately degrade), all carbon in the final product is assumed to be emitted back to the atmosphere. The definition of 'temporary' is the source of ongoing discussion. In the sensitivity analysis, for catalytic-conversion teams, a case is shown in which no end-use emissions are incurred.

The emissions produced by the two systems (CCU-based product system and incumbent product system) are compared to determine whether a CCU pathway is carbon-avoiding. Using our approach, a negative value in an LC-emissions result indicates that if the technology in question was not applied, i.e. the CO_2 generated by the power plant is released into the atmosphere and the CCU product is produced using the incumbent technology, then the GHG emissions into the atmosphere would be higher. Therefore, the technology deployed within the specified system results in an emissions reduction, making this an example of GHG mitigation. The negative value does not, however, imply that the system results in a net reduction of CO_2 in the atmosphere—i.e. it is not an example of carbon-dioxide removal (CDR) as described in [24], a common misinterpretation of negative values when substitution is applied in LCA. Life cycle guidelines for CO_2 utilization give the example of CDR as a system that captures CO_2 from the atmosphere, emits <1 kg CO_2eq/kg CO_2 utilized and sequesters the CO_2 emissions permanently after the product life cycle [23]. Other cases with variations in the CO_2 source (atmospheric or fossil sources) and whether CO_2 is emitted into the atmosphere or sequestered can be at best carbon-neutral. To determine whether a technology achieves CDR, a full system accounting of emissions is required, e.g. by using system expansion from the life cycle guidelines for CO_2 utilization [23]. With this approach, no credit is applied to the CCU system for CO_2 fed into the system and the CO_2 source is included in the system boundary, leading to a multi-product functional unit (including both the CO_2-based product and the product(s) from the facility producing the CO_2).

In this study, and to maintain consistency across the teams, allocation was selected to handle multi-product systems for teams producing multiple carbon-based products from converted CO_2. Allocation on a mass basis was selected for the base case and the impact of selecting other allocation methods (e.g. allocation on an energy or market basis) is explored in the sensitivity analysis. No emissions are allocated to non-carbon-based products (e.g. oxygen produced from electrolysis for hydrogen production).

The framework in Fig. 1 provides a summary of life cycle stages and was used as a basis of a data-collection template for all teams.

1.2 Technology Test Centre data and future scenarios

An external third-party organization collected technology-performance data from the demonstration facilities over the (up to) 30-day operating window for each competition team towards the end of the XPRIZE demonstration period [26]. Teams operated at different scales of conversion and not all teams operated over the full 30-day operating window. As the operating data collected at the Test Centre are confidential, results in this study are blended but have been verified by the external third party. More about the verification process can be found at https://350solutions.com/iso-14034-verified-technologies [27].

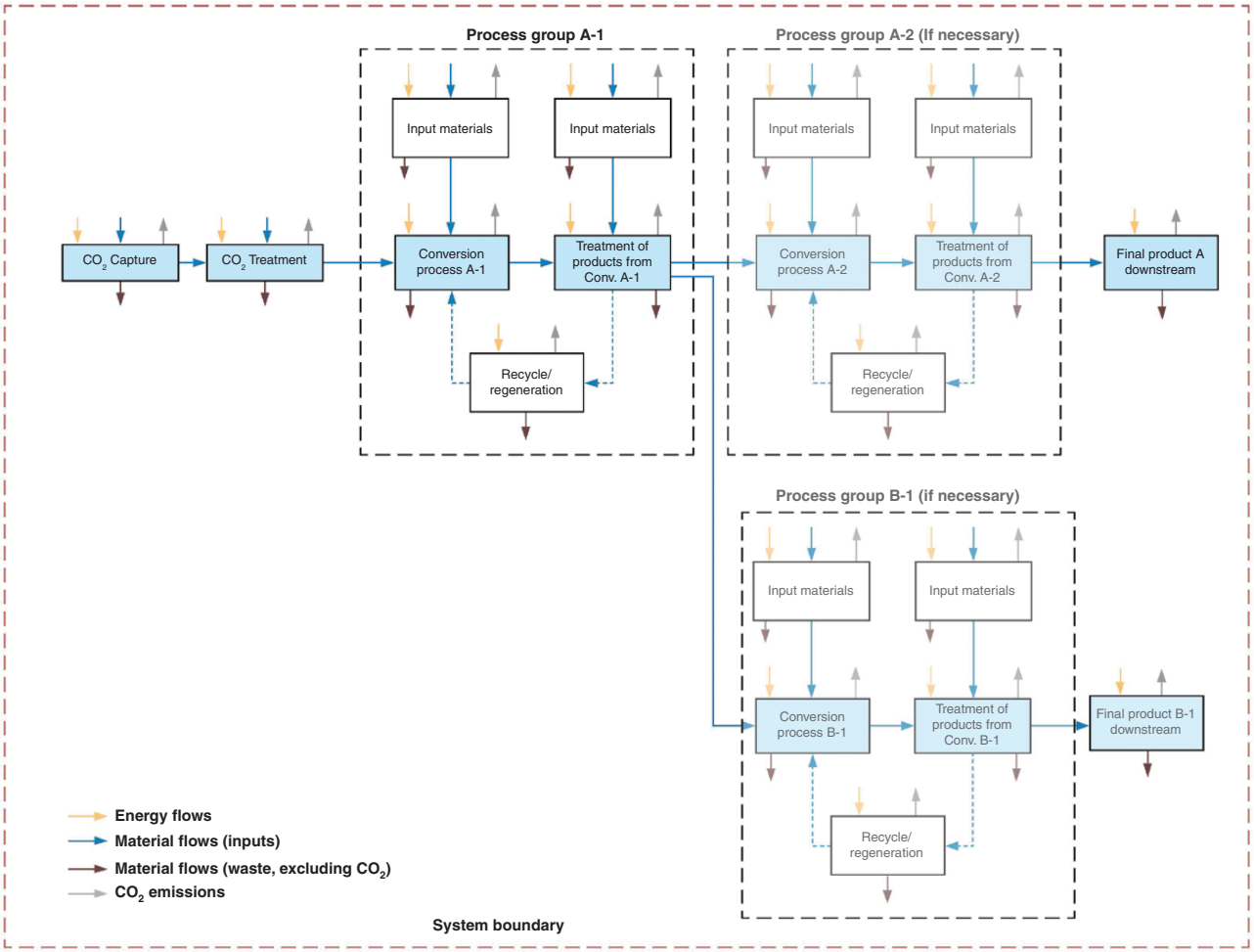


Fig. 1: Sample process diagram for life cycle of CO_2-derived products (adapted from [25]).

Where teams produced an intermediate product at the Test Centre (i.e. a product that requires processing to a final product to be taken to its end use), downstream emissions were estimated based on the best proxy data for the downstream processes in the following order of preference: (i) based on operating data for other demonstration plants operated by the team; (ii) based on modelling done by teams (e.g. separation energy requirements); or (iii) based on average or typical literature values (e.g. downstream conversion of the intermediate product produced at the Test Centre to a final product).

Future scenario technology data, or data collected at teams' sites outside the competition, were provided by the teams. Justification for the anticipated changes in technology performance for the teams are documented in the team submissions as part of the competition. Teams could propose performance changes by 2030 to both the conversion system and the downstream processing steps. The LCA team has not done any verification or validation of these anticipated performance changes; the intention of the future scenario is to indicate a set of plausible conditions (both the potential improvements anticipated in the next 10 years in technology performance and contextual changes such as an anticipated reduction in electricity-grid intensity) under which the team could be carbon-avoiding relative to an incumbent, rather than a projection of future performance. A summary of the range of CO_2-conversion rates achieved by teams at the Test Centre and the rates expected in the future scenario is presented in Table 1. More detailed process modelling to demonstrate how

Table 1: CO_2-conversion rates in the Test Centre and future scenarios

	CO_2 conversion (%)	
Pathway	Test Centre	Future
Mineralization	10.7–78.5	90–100
Catalytic conversion	11.1–40.2[a]	901–00[b]

Ranges presented show variability across teams (lowest to highest conversion rates) at the Test Centre during the competition and as projected by teams in the future scenario. At the Test Centre, demonstration scales varied from 0.00143–0.392 t CO_2/day (mineralization) and 0.014–0.481 t CO_2/day (catalytic conversion).

[a]Test Centre conversion rates for single-pass conversion (no recycle loop).

[b]Future scenarios assume that a net of 100% of unconverted CO_2 is recycled back to the conversion system due to the addition of a CO_2-recycle loop.

technology improvements could influence energy consumption and GHG emissions or changes to these or other similar technologies beyond 2030 is outside the scope of the current study but should be considered in future work.

1.3 Deployment context data

Consistent upstream emissions factors are applied across teams consuming the same materials or energy in their process. Due to travel restrictions at the time of the competition (2020), not all teams participating in the Wyoming track were able to travel to the Test Centre. For the competition, teams in Wyoming were assigned local emissions factors and carbon capture emissions based on the performance of the capture unit data supplied by the teams. In this study, to facilitate a fair comparison across teams operating at the two Test Centres, capture unit and electricity emissions factors from the Alberta track are employed for both the Alberta and Wyoming track teams (Table 2). The sensitivity analysis shows the impact on GHG emissions of locating all teams' processes in Wyoming, with a coal-intensive grid, compared to if the teams' processes were in Ontario, a lower-carbon grid and with different capture unit emissions, as well as different hydrogen-supply scenarios (Table 3), for teams that consume hydrogen.

For the future scenario, teams proposed changes to their existing or future deployment context (including expectations about changes to the emissions intensity of H_2 or electricity supply). Base-case carbon emission estimates are generated from the future deployment context parameters proposed by a team. A consistent set of future electricity- and hydrogen-supply scenarios is also presented in the sensitivity analysis.

1.4 Capture unit

The Alberta track teams obtained CO_2 from a monoethanolamine (MEA)-based post-combustion capture unit, supplying 25 tonnes per day of CO_2 from a natural-gas-fired power plant at the Alberta Carbon Conversion Technology Centre (ACCTC) [36]. Emissions resulting from carbon capture for all teams employing carbon capture (eight of the nine competition teams; one team utilized flue gas directly) are estimated based on the average performance of the capture unit over the 30-day demonstration period of the competition [26]. A low- and high-emissions intensity estimate for the Alberta track capture unit was developed by taking the 10th and 90th percentiles, respectively, of the intensity of heat and electricity consumed by the capture unit daily and the 90th and 10th percentiles, respectively, of the CO_2-capture efficiency of the capture unit.

The following inputs are included in the life cycle boundary of the capture unit: CO_2 released (i.e. not captured by the capture unit, calculated from the CO_2-capture efficiency), electricity consumption, natural gas combustion for heat supply and additional MEA required. The supply of these inputs for the team (base case), the low-sensitivity and the high-sensitivity scenarios are summarized in Table 4 below. A small amount of make-up MEA is typically required; this value is obtained from the literature [37] but contributes to a small fraction (<1%) of the

Table 2: Common electricity-supply emissions factors employed across teams

Location	Units	Average intensity	Description	Source
Test Centre (Alberta)	kg CO_2eq/kWh	0.695	Current Alberta average grid emissions	[28]
Test Centre low (Ontario)	kg CO_2eq/kWh	0.058	Current Ontario average grid emissions (low-carbon grid)	[29]
Test Centre high (Wyoming)	kg CO_2eq/kWh	0.936	Current Wyoming average grid emissions (high-carbon grid)	[30]
2030 Global electricity supply	kg CO_2eq/kWh	0.28	Electricity supply 2030 Global scenario from IEA 2°C projections	[31]
Solar photovoltaics + storage	kg CO_2eq/kWh	0.035	PV + 30% LMO battery storage in a high solar irradiation region (2300 kWh/m^2year)	[32]

Table 3: Common hydrogen-supply assumptions employed across teams consuming hydrogen

Location	Units	Average intensity	Description	Source
Bulk hydrogen supply to Test Centre	kg CO_2eq/kg H_2	10.62	Hydrogen from a steam–methane reformer without carbon capture and storage	[33]
Electrolyser efficiency (2030 H2 scenario)	kWh/kg H_2	39.9	Future H_2 electrolyser efficiency predicted by 2030	[34]
Electrolyser efficiency (NEL A series H2 scenario)	kWh/kg H_2	46	Current large-scale hydrogen electrolyser supply available in 2020	[35]

total capture unit emissions, even in the low-capture-unit emissions estimate. The impacts from MEA degradation were not included in the analysis.

To reflect the operating conditions at the Test Centre, electricity for the capture unit is assumed to be sourced from the Alberta grid (average emissions factor employed) for all teams and no capture of the CO_2 from the flue gas of the natural gas combusted to produce steam for the capture unit is included (i.e. the capture plant is not integrated into the power plant). An upstream emissions factor of 6.4 g CO_2eq/MJ natural gas is applied for the natural gas required to operate the capture unit, representing the western Canadian natural gas supply [38]. Capture unit emissions estimates are summarized in Table 5. The capture unit emissions from the ACCTC during the competition period are high relative to other deployed commercial capture units.

For the future scenario, a consistent capture unit emissions intensity of 0.18 kg CO_2eq/kg CO_2 captured is applied (versus the base-case Test Centre average of 0.748), reflecting anticipated improvements in capture unit performance between now and 2030, derived from the literature [39].

1.5 Incumbent selection

To determine whether a team is producing a carbon-avoiding product, an incumbent is defined by the current largest production method for producing the incumbent for the Alberta or Wyoming market today, or a similar proxy if those data are unavailable. While several of the teams have investigated producing a range of final products, for the purposes of estimating the carbon footprint of a single end use (e.g. concrete with specific strength properties, use of a product as a fuel or polymer), an incumbent is employed. Incumbent emissions were derived from the literature, aligned in terms of background system inputs (e.g. electricity) where possible to be produced in the same region as the Test Centre is located.

For mineralization teams, the incumbent product is defined as the final concrete product that aims to provide a similar service to the concrete containing mineralized CO_2 produced in the same region as the Test Centre at which the team is operating. As a result, although mineralization teams have an equivalent product (concrete), each mineralization team has a distinct incumbent that aligns with the properties of the concrete produced by the mineralization team.

The future incumbent is intended to account for changes anticipated in the incumbent between 2020 and 2030, e.g. due to changes in the deployment location proposed by the team or reductions in electricity-supply emissions intensity. Due to uncertainties and the large number of potential pathways for the incumbent to develop, the incumbent technology was not modified and only changes due to the deployment location or reduction in electricity-supply emissions intensity were considered. This can result in an overestimation in GHG emissions for the incumbent that needs to be accounted for when interpreting the results. For some incumbents, due to the aggregation of literature data, the impacts of reductions in electricity-grid emissions between 2020 and 2030 on the carbon footprint

Table 4: Capture unit inputs summary

Input	Units	30-Day average (base case)	Low value[a]	High value[a]
Electricity	kWh/kg CO_2 captured	0.13	0.12	0.16
Natural gas[b]	MJ/kg CO_2 captured	8.26	7.52	9.16
Capture efficiency	%	84.3	77.9	94.7
CO_2 in tail gas[c]	kg CO_2/kg CO_2 captured	0.186	0.0560	0.284
MEA[d]	kg MEA/kg CO_2 captured	0.0015	0.0015	0.0015

[a]Employed in sensitivity analysis.
[b]Consumed for solvent regeneration.
[c]Calculated from conversion efficiency.
[d]MEA supply emissions factor of 2.88 kg CO_2eq/kg MEA is applied, derived from [37]. Other inputs derived from ACCTC performance data [26].

Table 5: Breakdown of capture unit emissions intensities

Input	Units	30-Day average (base case)	Low value[a]	High value[a]
Electricity	kg CO_2eq/kg CO_2 captured	0.0886	0.0834	0.110
Natural gas	kg CO_2eq/kg CO_2 captured	0.469	0.427	0.520
CO_2 in tail gas[b]	kg CO_2eq/kg CO_2 captured	0.186	0.0560	0.284
MEA[c]	kg CO_2eq/kg CO_2 captured	0.0043	0.0043	0.0043
Capture-unit GHG	**kg CO_2eq/kg CO_2 captured**	**0.748**	**0.571**	**0.917**

[a]Employed in sensitivity analysis.
[b]Calculated from conversion efficiency.
[c]Derived from literature [37].

could not be accounted for. In these cases, a 10% reduction in the life cycle emissions intensity of the incumbent is predicted between 2020 and 2030. Further work should elaborate on the representation of possible changes to incumbent and competing systems.

2 Results

While a consistent framework was applied in evaluating the teams, caution should be taken to avoid drawing conclusions about the future potential of these technologies based on their Test Centre performance. The Test Centre was a deployment under industrial pilot conditions, representing both the core technology and the balance of the plant, at a larger scale than previous deployments for several of the technologies demonstrated. However, each technology demonstrated at the Test Centre operated at a different scale and the performance at the Test Centre was limited by several factors, including the constraints of the competition, a limited operating window with limited opportunities to optimize the operation of the technology and challenges in travelling to and obtaining materials for the technologies at the Test Centre during the 2020 COVID-19 pandemic. The Test Centre performance data are not expected to be representative of a team's optimal design or deployment characteristics. For example, several teams have deployed technologies in other pilots or intend to implement in future deployments a CO_2-recycle loop to increase their net conversion rates, which would substantively change the emissions of their systems. The Test Centre locations were also not optimal deployment conditions for many teams (e.g. due to the largely fossil-based electricity grids in Alberta and Wyoming). The technologies are also at varying stages of commercial development and deployment. Thus, direct comparisons across Test Centre pathways at different technology-readiness levels (TRLs), deployment scales, etc. are neither intended nor accurate. Future larger-scale deployments of these technologies will likely take advantage of increased efficiencies due to larger production scales, learning by doing, more optimization of the supply of lower-carbon inputs, etc., which were considered in the future case scenario to represent existing (outside of the competition) or near-term deployments by the teams. The analyses presented in subsequent sections are blended to show the carbon footprints for each major technology pathway: mineralization and catalytic conversion. The ranges of performance for each technology pathway demonstrates the range of emissions of the teams operating at the Test Centres and the primary drivers of emissions at that deployment scale and under Test Centre conditions. This grouping also helps to avoid drawing firm conclusions about individual technologies given that they are at different stages of development and some are still at early stages (i.e. have opportunities to improve the design and deployment).

2.1 Mineralization pathway

For teams producing concrete, due to the variety of concretes and their intended applications, both concretes containing mineralized CO_2 and the incumbent pathways vary substantially in their GHG emissions across teams. All efforts were made to characterize the carbon impact of resultant differences in the strength, durability or density of the concrete and possible changes to the material requirements for building in the products from mineralization as compared to the closest incumbent. As shown in Fig. 2a, on a per-kg of concrete basis, concrete production (supply of cement, aggregate, etc.) was the primary driver of emissions, rather than the conversion process itself, due to the relatively small contribution of CO_2-based products relative to other inputs into the concrete. However, teams were able to demonstrate emissions comparable to those of incumbent concrete in several cases at the Test Centre, even under the non-idealized deployment conditions at the Test Centre. For several teams, emissions reductions were achieved by displacing cement, a relatively emissions-intensive input, in the concrete mix, rather than the direct impact of mineralizing CO_2.

Fig. 2b shows the sensitivity of Test Centre emissions estimates to variations in the input parameters. Variations in emissions are shown relative to the net Test Centre emissions estimate. Base-case input-parameter values, those employed in estimating net emissions, are given in parentheses after the parameter value in the y-axis labels. The bars show how the net Test Centre emissions would change if parameters were varied from the low to high values shown at the ends of the bars. Parameters are colour-coded by type, whether they are associated with the deployment context (e.g. GHG intensity of electricity supply, in green) or the technology performance (e.g. electricity demand, in purple). For the example mineralization team presented, Test Centre results are most sensitive to the electricity consumed and deployment location (i.e. grid-emissions intensity employed). The purple bar in Fig. 2b shows that in near-term deployments, reducing the electricity demand is expected to decrease the net emissions by 27%. The approach for crediting emissions from the CO_2 converted, in the base case, assumes that the system receives a credit of 100% of the CO_2 fed into the system as substitution is applied (ranges shown in the first column of Fig. 2a). Varying the accounting method employed can impact the net emissions in this pathway by ≤16%. This shows the impact of LCA methodological choices (e.g. the allocation method) and the analysis framework on assessments of the environmental impacts from these systems.

2.2 Catalytic-conversion pathway

Catalytic conversion pathway emissions estimates at the Test Centre (Fig. 3a) show extreme variability across pathways and none competes with the incumbent based on their Test Centre performance when powered

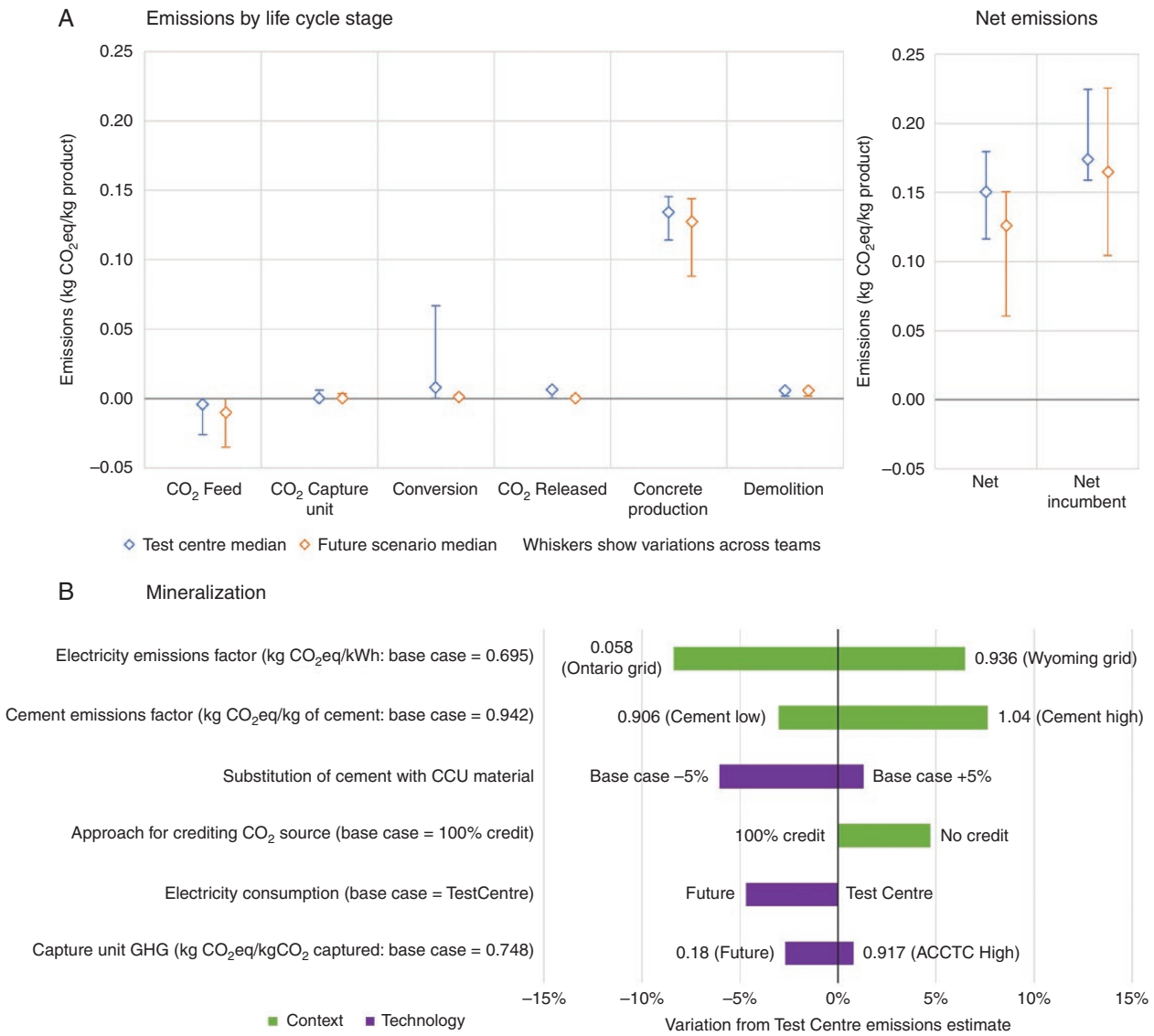


Fig. 2: (a) Shows cradle-to-grave Test Centre (blue) and future scenario (orange) carbon-footprint estimates per kg of product for mineralization teams. Whiskers show the range of emissions across teams while diamonds show the median emissions for each life cycle stage across teams. Median values do not directly correspond to any one team, so the median values do not sum to the net emissions. Sensitivity to variability in technology performance (purple) and deployment context (green) shown in (b) for an example mineralization team.

using fossil-fuel-derived electricity. However, each of the catalytic-conversion technologies was nonetheless able to demonstrate a carbon-avoiding pathway relative to an incumbent in a future scenario. As discussed above, there were significant constraints on the companies at the Test Centres, many of whom were unable to demonstrate their optimal performance for multiple reasons based on siting, cost, rules, COVID issues, etc. It is also helpful to note that many of the pathways in this category are at an early stage of development. As such, the potential for improvement is greater than the relatively constrained future scenarios considered in this study. Having said this, powering the chemical conversion of CO_2 with energy sources that have a comparatively high carbon intensity will thermodynamically always result in a less efficient process than direct use of the chemical energy in the fossil fuels. This emphasizes the need for chemical CO_2-conversion technologies to be powered by renewable or low-carbon energy sources. For these teams, one driver of improved technology performance expected by the teams is anticipated improvements in CO_2-conversion rates, as well as the addition of a recycle loop for unconverted CO_2 (Table 1 shows Test Centre and anticipated future CO_2-conversion rates). This can also be seen in Fig. 3a in the comparison between the Test Centre and future scenarios, where the net CO_2 fed into the system decreases (on a per-kg product basis) due to higher conversion rates, leading to a reduction in emissions from both the capture unit and CO_2 released. Alberta has a fossil-dominated electricity grid with an emissions intensity of 0.695 kg CO_2eq/kWh [28], where CO_2-conversion processes, if deployed, would be unlikely to source their electricity from the grid. Previous studies

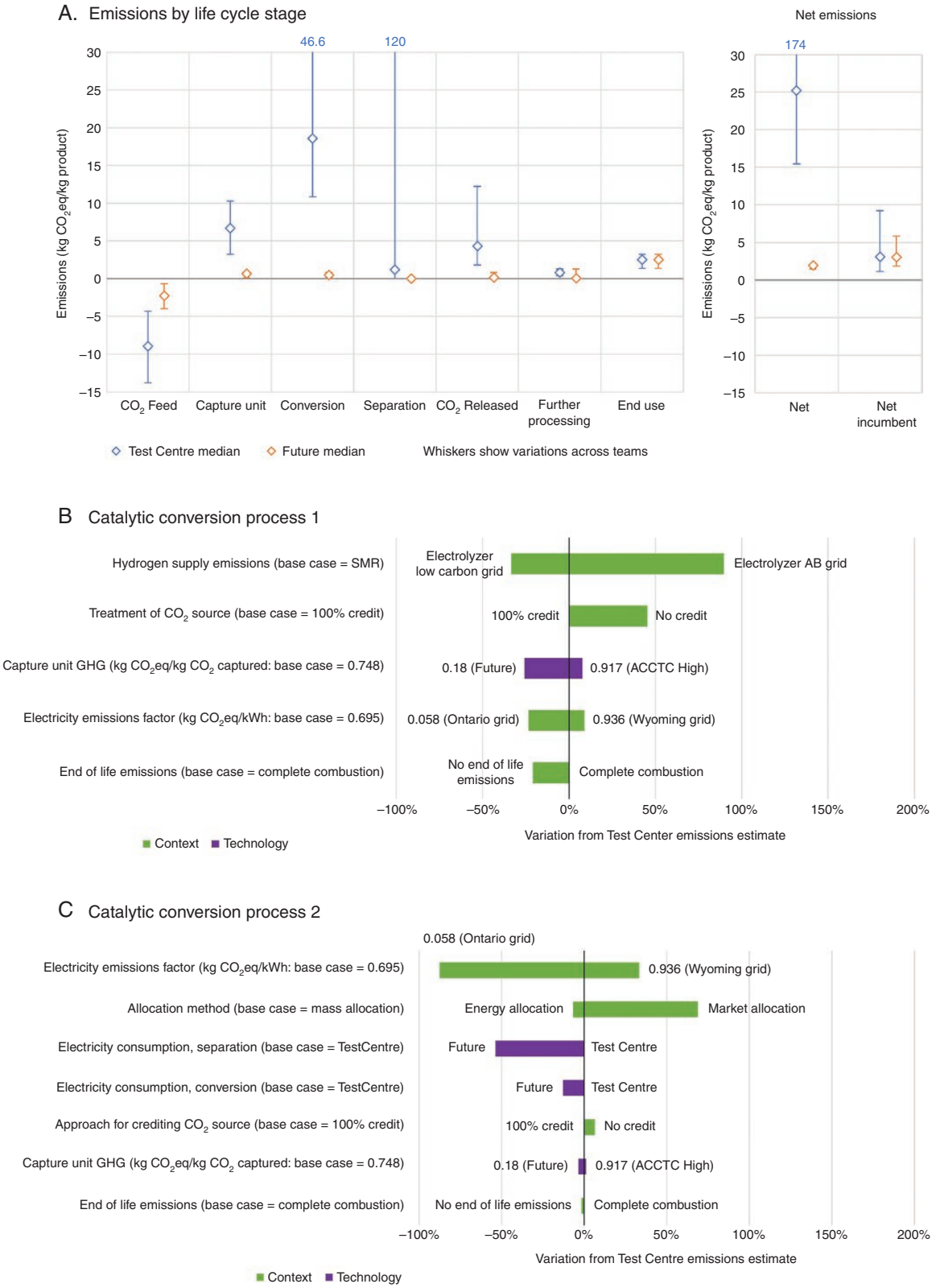


Fig. 3: (a) Shows cradle-to-grave Test Centre (blue) and future scenario (orange) carbon-footprint estimates per kg of product for catalytic-conversion teams. Whiskers show the range of emissions across teams while diamonds show the median emissions for each life cycle stage across teams. Median values do not directly correspond to any one team, so the median values do not sum to the net emissions. Sensitivity to variability in technology performance (purple) and deployment context (green) shown in (b) and (c) for two catalytic-conversion teams as examples to show the types of drivers of variability and uncertainty across catalytic-conversion teams.

have suggested (e.g. [6, 17]) that low-carbon electricity and hydrogen are required for fuels and chemicals derived from CO_2 to be competitive with current fossil-based processes. The current analysis suggests that careful selection of both the pathways and the deployment context is required to ensure that emissions reductions are achieved by deploying these technologies.

Lower emissions have been observed from other commercially deployed MEA-based capture units than the one operating at the Alberta Test Centre (0.748 kg CO_2eq/kg CO_2 captured). Since many teams had lower CO_2-conversion rates at the Test Centre and did not employ a CO_2-recycle loop or did not have theirs online during the XPRIZE testing period, the emissions from capturing CO_2 from the power plant for these teams were higher than those in future implementation scenarios. Emissions from the separation of products from the conversion system also contributed substantially to the net emissions of the system for several teams; with higher conversion rates at other deployments and with improved separation technologies, the emissions from this stage showed major improvements in the future case. However, this demonstrates the importance of taking a full-system perspective in assessing these technologies rather than focusing exclusively on the conversion system itself.

Sample sensitivity analyses for two catalytic-conversion-pathway teams are shown in Fig. 3b and c. For the team represented in Fig. 3b, electricity consumed directly by the process is relatively low, so the impact of the emissions intensity of the electricity supply is relatively low compared to the impact of the emissions intensity of hydrogen supplied to the process, which at the Test Centre was purchased from a supplier producing hydrogen via steam–methane reforming. Therefore, sourcing the hydrogen from an electrolysis process with low-carbon electricity can reduce the pathways emissions by 36%. Of the five parameters varied in the sensitivity analysis, four are related to the deployment context rather than the performance of the technology itself. For the team represented in Fig. 3c, the intensity of the electricity consumed has the largest impact on the pathway emissions. As the team produced two primary products at the Test Centre, at a mass ratio of 7.5:1, the choice of allocation method is the second most impactful parameter, followed by the conversion rates and efficiency of the separation processes. Emissions estimates derived directly from Test Centre performance data should not be employed to eliminate this pathway but used as a guide to target where the biggest reductions in GHG emissions are achievable through technology improvements, the application of emerging processes and careful selection of deployment conditions. In addition, catalytic conversion for chemicals production has been identified by others (e.g. [40, 41]) as a promising approach for using excess electricity (e.g. intermittent renewables). Exploration of the potential additional benefits from specific deployment scenarios is beyond the scope of this work but should be considered in future studies.

2.3 General insights about the LCA of CCU technologies and future work

If deployed under the same conditions as the Test Centre (e.g. sourcing electricity from the Alberta grid), all teams (current and future) resulted in net-positive emissions (where net negative in this case is defined relative to a reference pathway so is not an indicator of a net removal of CO_2 from the atmosphere). A net negative here would still not qualify as a carbon-removal technology as defined in [24] when the combustion of final products (for catalytic-conversion pathways) was considered.

Another assumption varied across all pathways in the sensitivity analysis is the approach for crediting emissions from the CO_2 source. In this study, the base case assumes that the conversion system receives a credit for all CO_2 converted (labelled as 'CO_2 feed' in Figs 2a and 3a). The sensitivity shows an alternative in which no credit is given to the conversion system for the CO_2 converted by the system. This could for example represent how a CCU system may be treated if a new natural-gas-fired power plant is under consideration, so the counterfactual to the CCU system would not include CO_2 otherwise emitted by the power plant. In this case in which no credit is applied to the CCU system, the CO_2 is treated as a feedstock to the conversion process, but the CCU system receives no benefit from capturing the CO_2. Alternatively, the system could be expanded to include multiple functional units (e.g. electricity produced by the power plant) to explore how assumptions surrounding the treatment of the CO_2 source affects the performance of CCU technologies relative to incumbent processes. This is outside the scope of the current work.

For mineralization pathways, an incumbent concrete product was selected for each team that is expected to provide an equivalent service to the concrete containing mineralized CO_2. The GHG emissions reductions of the concrete were attributable to the mineralization of CO_2 and reductions in cement needed to produce concrete of an equivalent strength for a similar application. However, mineralized CO_2 can impact other factors (e.g. strength, workability, set time, durability, regulatory and cost considerations) that could impact the application of concretes containing mineralized CO_2 with resultant effects on net GHG emissions [16]. While every effort was made to account for this, future work should integrate LCA with additional analysis to consider how the impacts of the mineralization of CO_2 into building materials could impact other concrete properties and could thereby influence the life cycle emissions of these final products. In addition, the impacts of actively mineralizing CO_2 on the natural mineralization of CO_2 into concrete during the use and demolition of concrete should also be further explored. For thermochemical and electrochemical pathways, this study compared CCU technologies to current incumbent pathways. Comparison to other GHG-mitigation opportunities in the sectors targeted by CCU technologies should be incorporated into future work to assess the effectiveness of CCU technologies

relative to other mitigation options. Additionally, this study focused on estimating the emissions from the conversion of CO_2 as demonstrated by teams at the Test Centre. The downstream applications and potential end uses selected in this study represent a subset of possible uses for CO_2-derived products. Future work should develop additional downstream scenarios to look for synergies between conversion and downstream uses.

This study provides an estimate of the carbon footprint of the competition teams as they performed at the Test Centre and a preliminary estimate of future carbon footprints achievable through more favourable deployment contexts and incremental technology improvements. The analysis presented does not account for the scale, TRL, development trajectory, deployment context or effect of more transformational technology improvements on carbon footprints. Future assessments of these technologies should account for these aspects as these technologies are further developed and deployed.

3 Conclusions

This study discusses the assessment of the carbon-footprinting exercise completed for the Carbon XPRIZE competition team finalists, providing a snapshot in time and under one set of conditions at one facility. The exercise helps to demonstrate the wide and important variability in GHG emissions of CO_2-based products relative to primarily fossil-based incumbents, both at the competition Test Centres and in anticipated near-term (2030) future applications. Mineralization pathways were more readily able to show GHG improvements over the incumbents, while the pathway for catalytic technologies rely on more significant technological and contextual improvements. This is explained in part by the fact that many of these technologies are at early stages of development and therefore there is room for further innovation. This can be seen in that the catalytic-conversion technologies were able to demonstrate a carbon-avoiding pathway relative to an incumbent in future scenarios for all teams.

LCA methods were first developed to evaluate commercially deployed technologies. This exercise demonstrates the challenges in conducting LCAs of carbon-conversion technologies in their current form, as technologies are at varying levels of commercialization and due to the range of possible pathways, products and end uses for converted CO_2. Despite this, LCAs of early-stage technologies can provide directional insights to aid in prioritizing emissions-reduction opportunities. As new technologies are developed and deployed, iteratively estimating the carbon footprint can further aid in the prioritization of research activities

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Conflict of interest statement

None declared.

References

[1] Mac Dowell N, Fennell PS, Shah N, *et al*. The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change*, 2017, 7:243–249.

[2] Abanades JC, Rubin ES, Mazzotti M, *et al*. On the climate change mitigation potential of CO_2 conversion to fuels. *Energy & Environmental Science*, 2017, 10:2491–2499.

[3] Dairanieh I, David B, Mason F, *et al*. *Carbon Dioxide Utilization (CO2U)—ICEF Roadmap 1.0*. Tokyo: ICEF Innovation Roadmap Project, 2016.

[4] Kätelhön A, Meys R, Deutz S, *et al*. Climate change mitigation potential of carbon capture and utilization in the chemical industry. *Proceedings of the National Academy of Sciences of the United States of America*, 2019;116:11187–11194.

[5] Bergerson JA, Brandt A, Cresko J, *et al*. Life cycle assessment of emerging technologies: evaluation techniques at different stages of market and technical maturity. *Journal of Industrial Ecology*, 2020, 24:11–25.

[6] Thonemann N. Environmental impacts of CO_2-based chemical production: a systematic literature review and meta-analysis. *Applied Energy*, 2020, 263:114599.

[7] Sternberg A, Jens CM, Bardow A. Life cycle assessment of CO_2-based C1-chemicals. *Green Chemistry*, 2017, 19:2244–2259.

[8] Bongartz D, Doré L, Eichler K, *et al*. Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide. *Applied Energy*, 2018, 231:757–767.

[9] Cuéllar-Franca R, García-Gutiérrez P, Dimitriou I, *et al*. Utilising carbon dioxide for transport fuels: the economic and environmental sustainability of different Fischer–Tropsch process designs. *Applied Energy*, 2019, 253:113560.

[10] Fernández-Dacosta C, Shen L, Schakel W, *et al*. Potential and challenges of low-carbon energy options: comparative assessment of alternative fuels for the transport sector. *Applied Energy*, 2019, 236:590–606.

[11] Liu CM, Sandhu NK, McCoy ST, *et al*. A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production. *Sustainable Energy Fuels*, 2020, 4:3129–3142.

[12] van der Giesen C, Kleijn R, Kramer GJ. Energy and climate impacts of producing synthetic hydrocarbon fuels from $CO(_2)$. *Environmental Science & Technology*, 2014;48:7111–7121.

[13] Deutz S, Bongartz D, Heuser B, *et al*. Cleaner production of cleaner fuels: wind-to-wheel—environmental assessment of CO_2-based oxymethylene ether as a drop-in fuel. *Energy & Environmental Science*, 2018, 11:331–343.

[14] Koj JC, Wulf C, Zapp P. Environmental impacts of power-to-X systems: a review of technological and methodological choices in life cycle assessments. *Renewable and Sustainable Energy Reviews*, 2019, 112:865–879.

[15] Ostovari H, Sternberg A, Bardow A. Rock 'n' use of CO_2: carbon footprint of carbon capture and utilization by mineralization. *Sustainable Energy Fuels*, 2020, 4:4482–4496.

[16] Ravikumar D, Zhang D, Keoleian G, *et al*. Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. *Nature Communications*, 2021, 12:855.

[17] Ravikumar D, Keoleian G, Miller S. The environmental opportunity cost of using renewable energy for carbon capture and utilization for methanol production. *Applied Energy,* 2020, 279:115770.
[18] De Luna P, Hahn C, Higgins D, *et al*. What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science,* 2019, 364:eaav3506.
[19] Hoppe W, Thonemann N, Bringezu S. Life cycle assessment of carbon dioxide-based production of methane and methanol and derived polymers: LCA of CO_2-based chemicals. *Journal of Industrial Ecology,* 2018, 22:327–340.
[20] Chauvy R, Meunier N, Thomas D, *et al*. Selecting emerging CO_2 utilization products for short- to mid-term deployment. *Applied Energy,* 2019, 236:662–680.
[21] XPRIZE Foundation. *NRG COSIA Carbon XPRIZE Draft Competition Guidelines, Version 1.4*. 2016. https://www.xprize.org/prizes/carbon/guidelines (10 August 2021, date last accessed).
[22] Heijungs R, Allacker K, Benetto E, *et al*. System expansion and substitution in LCA: a lost opportunity of ISO 14044 amendment 2. *Frontiers in Sustainability,* 2021, 2:692055.
[23] Zimmerman A, Wunderlich J, Buchner G, *et al*. *Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO_2 Utilization. Global CO_2 Initiative*. Ann Arbor, MI: University of Michigan, 2018.
[24] Fuss S, Lamb WF, Callaghan MW, *et al*. Negative emissions—part 2: costs, potentials and side effects. *Environmental Research Letters,* 2018, 13:063002.
[25] Nishikawa E, Ahmad S, Gaona A, *et al*. *LCA Estimate Model for CCU*. https://github.com/LCAofCCU-UCalgary/LCA-Estimate-Model-for-CCU-Spreadsheet (10 August 2021, date last accessed).
[26] 350Solutions. *Verification Statement: ASCO CO_2 Stack Gas Recovery Plant*. https://350solutions.com/wp-content/uploads/2021/05/350Solutions_-Capture-VS_XPB06_Verification_4292021-FINAL.pdf (10 August 2021, date last accessed).
[27] Hansen T, McCabe K, Chatterton B, *et al*. Integrating the ISO 14034 standard as a platform for carbon capture & utilization technology performance evaluation. *Clean Energy,* 2021. doi:10.1093/ce/zkab033.
[28] Environment and Climate Change Canada. *National Inventory Report 1990–2018: Greenhouse Gas Sources and Sinks in Canada*. Ottawa: Environment Canada, 2018.
[29] Pereira L, Posen ID. Lifecycle greenhouse gas emissions from electricity in the province of Ontario at different temporal resolutions. *Journal of Cleaner Production,* 2020, 270:122514.
[30] US EPA. *Emissions & Generation Resource Integrated Database (eGRID)*. US EPA, 2020. https://www.epa.gov/egrid (26 August 2021, date last accessed).
[31] Deutz S, Bardow A. How (carbon-) negative is direct air capture? Life cycle assessment for industrial temperature-vacuum swing adsorption process. *ChemRxiv,* 2020. doi:10.26434/chemrxiv.12833747.v1.
[32] Raugei M, Leccisi E, Fthenakis VM. What are the energy and environmental impacts of adding battery storage to photovoltaics? A generalized life cycle assessment. *Energy Technology,* 2020, 8:1901146.
[33] Spath PL, Mann MK. *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming, NREL/TP-570–27637*. Golden, CO: National Renewable Energy Laboratory, 2000.
[34] Dotan H, Landman A, Sheehan SW, *et al*. Decoupled hydrogen and oxygen evolution by a two-step electrochemical–chemical cycle for efficient overall water splitting. *Nature Energy,* 2019, 4:786–795.
[35] Nel Hydrogen. *Nel A-Series Atmospheric Alkaline Electrolyser*. https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/ (10 August 2021, date last accessed).
[36] InnoTech Alberta. *Alberta Carbon Conversion Technology Centre (ACCTC)*. https://innotechalberta.ca/research-facilities/alberta-carbon-conversion-technology-centre-acctc/ (10 August 2021, date last accessed).
[37] Uusitalo V, Väisänen S, Inkeri E, *et al*. Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis. *Energy Conversion and Management*, 2017, 134:125–134.
[38] Senobari Vayghan E. Greenhouse gas emissions from natural gas development in western Canada: a gap analysis. 2016. https://prism.ucalgary.ca/handle/11023/3140 (26 August 2021, date last accessed).
[39] NTUA. *HELMETH—D5.2: Final LCA Report HELMETH Concept System 1–33: Deliverable 5.2: Final LCA Report*. Athens, Greece: National Technical University of Athens, 2017.
[40] Sternberg A, Bardow A. Power-to-what? Environmental assessment of energy storage systems. *Energy & Environmental Science,* 2015, 8:389–400.
[41] Roh K, Chung W, Lee H, *et al*. Impacts of deploying co-electrolysis of CO_2 and H2O in the power generation sector: a case study for South Korea. *Energy Reports,* 2020, 6:761–770.