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Impact of background systems on carbon capture and utilization pathways to produce fuels/chemicals in Canada

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Carbon capture and utilization (CCU) to produce fuels and chemicals is a promising strategy to reduce greenhouse gas (GHG) emissions. However, net GHG emissions depend heavily on required electricity, hydrogen, and heat, collectively known as background system inputs. We model the cradle-to-gate GHG emissions for 13 chemicals and fuels produced through 20 CCU pathways (8 at or beyond demonstration scale [*e.g.*, methanol from hydrogenation], 5 under lab-scale development [*e.g.*, formic acid from electrochemical reduction], and 7 at research phase [*e.g.*, methane from photocatalytic reaction]), using 12 background system scenarios for Canada from 2020–2050. The CCU chemicals and fuels are compared against the dominant incumbent pathways with the same harmonized background system. Results show that GHG emissions intensities for most of the CCU pathways vary substantially with the background system, with the GHG intensity of electricity being the most impactful factor followed by variation in provision of hydrogen and heat. While low GHG intensity electricity is crucial, it does not guarantee the CCU pathways will have lower GHG intensity than incumbents. Most incumbent pathways are also sensitive to background system changes, thus using fixed values to represent the emissions intensities of incumbent pathways is insufficient. Out of the 20 CCU pathways, 5 have the potential for lower emissions intensity than incumbents in all 2020 scenarios, but only one is currently technically mature and could be deployed at demonstration scale.

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1. Introduction

Carbon capture and utilization (CCU) is recognized as a potential strategy to reduce greenhouse gas (GHG) emissions in chemicals and fuels production.[1] However, many CCU technologies require energy or emission-intensive inputs including electricity, hydrogen, heat, and chemical feedstock. Kätelhön *et al.* (2019) estimated that to reduce 3.5 Gt CO_2e emissions annually in 2030 from chemical production through implementing CCU would require an additional 18 Petawatt hours (PWh) of low-carbon electricity, 55% of the projected 2030 global electricity output.[2] Allocating this amount of electricity to CCU may be impractical given constraints to rapidly increasing electricity generation capacity. Thus, maximizing GHG emissions reductions requires prioritizing CCU pathways with the greatest GHG reduction potential while considering factors such as cost, infrastructure, markets, and local context, among others.

Previous life cycle assessments (LCAs) have evaluated the climate benefits of many CCU pathways.[3] Across a wide range of pathways examined, GHG emissions associated with CCU chemical and fuel production pathways are highly sensitive to the sources and emissions intensities of electricity, hydrogen, heat, and steam inputs to the processes.[2,4–7] These external parameters that affect the environmental impact of investigated technologies can be categorized as part of the background system.[8,9] Studies have also shown that changes in the background system can significantly affect the environmental impact of emerging decarbonization technologies.[10–12] As the background system affects different CCU pathways to different extents, the ranking of CCU pathways with respect to their GHG emissions intensity can vary depending on the background system.[11,12] Similarly, for an individual pathway, the qualitative conclusion about the climate benefits may vary under different background systems.[13,14]

While previous research has investigated the impact of background systems on CCU pathways, there is a lack of consideration of the impact of background systems on the incumbent pathways, which are producing the products that the CCU pathways would be expected to displace. When quantifying GHG emissions of CCU pathways and comparing them with those of incumbent pathways, many studies assume that the emissions of incumbents remain constant over time.[4,15,16] However, inputs (*e.g.*, electricity, hydrogen) are also important for incumbent pathways[17,18] and changes to these inputs may also result in changes in GHG emissions of these pathways. For

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fair comparisons between CCU pathways and incumbent pathways, it is crucial to model the impact of the background system on both categories of pathways.

Given the growing global interest in CCU, various regions are exploring implementation strategies.[19] The Government of Canada has increased investment in Research and Development (R&D)[20] and tax incentives[21] for CCU and storage (CCUS) technologies, and included them in the 2030 Emissions Reduction Plan.[22] As of 2025, seven CCUS projects are operating in Canada and all are for enhanced oil recovery (EOR) or geological storage,[23] indicating considerable potential for the expansion of CCU. Among the various CCU pathways with different final products and environmental performance, industry leaders, funding agencies and policymakers must have accurate techno-economic and environmental information to prioritize specific pathways for investment and, ultimately, for deployment. While a variety of factors including cost, infrastructure requirements and market demand will ultimately determine which pathways are deployed, a critical first step is to assess how pathways perform in terms of their GHG intensities. The study objective is to identify promising CCU pathways, from a GHG mitigation perspective, for producing fuels and chemicals in Canada from 2020–2050 through evaluating the impact of background systems on both CCU and incumbent pathways. We model the cradle-to-gate GHG emissions associated with producing 13 chemicals and fuels through 20 CCU pathways, utilizing 12 background system scenarios, within the Canadian context. This study focuses on CCU pathways for producing chemicals and fuels, as these sectors have high energy demand and offer substantial opportunities to displace fossil-derived feedstocks. The CCU chemicals and fuels are compared against the dominant incumbent pathways with the same harmonized background system.

2. Methods

2.1 Overview

The study scope includes a CCU pathway module and an Incumbent pathway module (see Fig. 1). Within the CCU module, we consider 13 products produced through 20 CCU pathways (*e.g.*, methanol from hydrogenation; carbon monoxide from reverse water gas shift) that have different expected years to commercialization (see Section 2.3.2 for details on the selection of the pathways). The CO_2 utilized in those 20 pathways is assumed to be captured from the atmosphere using direct air capture (DAC). In the Incumbent pathway module, we consider 13 dominant incumbent pathways to produce an equivalent set of investigated chemicals and fuels. These incumbents are produced either from fossil fuel (*e.g.*, methanol from steam methane reforming [SMR]) or biomass (*e.g.*, ethanol from corn and wheat), depending on the dominant production method for these products in Canada (see Section 2.4 for details). The life cycle inventory data for the CCU (see S1.1) and incumbent pathways (see S1.2) are obtained from existing literature[6,16,24–37] and databases.[38,39] We focus on electricity, hydrogen and heat as the three common background system inputs to all pathways considered. We evaluate changes in GHG intensity of these three inputs over time under 12 different scenarios and assess the subsequent impacts on life cycle GHG emissions intensity of the investigated pathways. Other inputs such as water and catalysts are also considered when calculating GHG emissions but are assumed to have constant GHG intensities from 2020 to 2050. See Section 2.1–2.5 for additional information about the functional unit, data sources, and assumptions.

2.2 Functional unit

The functional unit of CCU products can be end product-based (*e.g.*, 1 kg product) or input-based (*e.g.*, 1 kg CO_2 utilized). Most LCAs use an end product-based functional unit, which allows for estimating absolute emission reductions when switching to a CCU product.[4,40–42] However, to compare the environmental impacts of CCU pathways producing different products, it is helpful for the functional unit to be the same for all products and, thus, input-based. Carbon dioxide is a necessary input for all CCU pathways, thus a functional unit of 1 kg of utilized CO_2 allows us to compare the CCU pathways.[15,16] For studies included in this assessment that use other functional units, we harmonized them to 1 kg of utilized CO_2 based on the relationship between the default functional unit in the original study and the amount of utilized CO_2 per functional unit.

2.3 CCU pathway module

2.3.1 Carbon capture. Carbon dioxide is assumed to be captured from the atmosphere using the lowest emission high temperature-DAC configuration from Keith *et al.*, which represents Carbon Engineering's commercial-scale process design informed by pilot-plant configuration in Squamish, Canada.[43] DAC is chosen instead of post-combustion capture primarily because it is not constrained by the potentially declining availability of concentrated industrial CO_2 streams as other sectors decarbonize.[44] As this work evaluates pathways under changing energy systems, DAC may serve as a relevant long-term option for scalable CO_2 supply. The selected configuration represents a commercial-scale design in which grid electricity provides all power not supplied by the steam cycle driven by the steam slaker,[43] thereby enabling assessment of how decarbonization of the background energy system would affect DAC's GHG emissions. Keith *et al.* reported the following input requirements to capture, compress, and separate 1 ton of CO_2: 5.25 GJ heat and 360 kWh of electricity,[43] which fall within the range of a typical high temperature-DAC system.[45] Due to the possible loss of CO_2 in the conversion process, the amount of captured CO_2 needed for the conversion process is equal to or higher than the quantity of utilized CO_2, depending on the CO_2 conversion efficiency of the different pathways (see Table S1).

2.3.2 Carbon utilization. To evaluate the GHG emissions intensities of CCU pathways with harmonized background systems, we first select a set of CCU pathways to be investigated. de Kleijne *et al.* conducted a systematic literature review of published LCAs of CCU pathways, which resulted in the most comprehensive literature database of CCU pathways at the time of writing.[15] That study included 30 studies covering 44

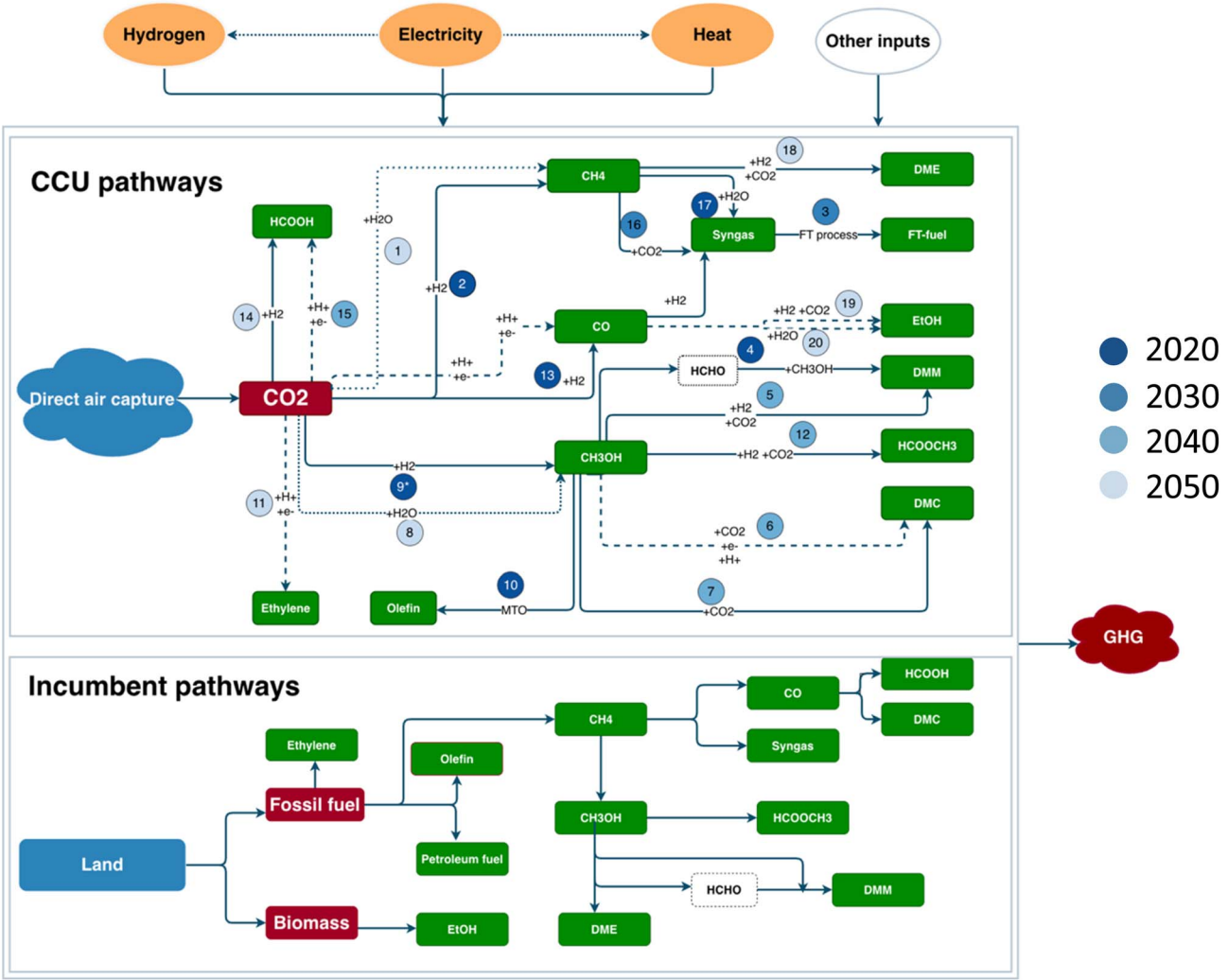

Fig. 1 Scope of CCU and incumbent pathways for producing fuels and chemicals assessed in the study. In the CCU pathway module, 13 products are examined (represented in green rectangles), and 20 specific pathways (represented by circles with varying shades of blue indicating the estimated year to commercialization as of 2024). The numbering of pathways (1–20) matches the order of pathways in Table S1. Solid, dashed, and dotted lines represent thermochemical, electrochemical, and photochemical pathways, respectively. In the Incumbent pathway module, 13 products produced from dominant incumbent pathways are examined (represented in green rectangles). Three dynamic background system parameters are represented in orange ellipses. Other inputs such as water and catalysts are also considered, but their GHG intensities are assumed to remain constant from 2020 to 2050. Products include methane (CH_4), Fischer–Tropsch fuels (FT-fuel, a blend of naphtha, kerosene, gasoil and base oil with a heating value of 43.2 MJ kg^{-1}), dimethyoxymethane (DMM), dimethyl carbonate (DMC), methanol (CH_3OH), olefins (mixture of ethylene, propylene and butylene), ethylene (single product), methyl formate ($HCOOCH_3$), carbon monoxide (CO), formic acid (HCOOH), syngas, dimethyl ether (DME), and ethanol (EtOH). Details for each numbered pathway are available in the SI. Methanol produced from pathway 9, marked with an asterisk "*", is used as an intermediate to produce other chemicals (*e.g.*, DMM, DMC).

conversion pathways and 28 unique final CCU products (1 for direct use, 2 for enhanced hydrocarbon recovery, 16 for fuels and chemicals, and 9 for mineral carbonates and construction materials). As our study focuses on the use of CCU in the fuels and chemicals industries, we screen the 26 CCU pathways associated with the 16 fuels and chemicals in de Kleijne *et al.* and select 18 pathways producing 12 products. We source inventory data for these pathways from the references cited in de Kleijne that report a comprehensive life cycle inventory.[6,16,24–36] Due to the large market size of ethanol,[3] we also consider two CCU pathways for ethanol production,[46] which were not included in de Kleijne *et al.* The descriptions of the 20 pathways containing the product, process, chemical reaction formula, and input are in Table S1.

Of the 20 pathways, 2 use photochemical conversion, where final products are produced using sunlight, water, and desensitized semiconductors. Five pathways use electrochemical conversion, where CO_2 is reduced at atmospheric temperature using electricity. The remaining pathways use thermochemical conversion involving single or multiple reaction steps. For the latter, chemicals produced from earlier steps are used as the intermediates in the later steps (*e.g.*, methanol is produced from CO_2 and then used for dimethyl carbonate production). Methane and methanol are the most common intermediates (see Fig. 1). Unlike previous work where methanol and methane

intermediates for CCU-based chemicals came from fossil feedstock,[4] we assume these intermediates are produced through CCU pathways. Specifically, we assume methane is produced from the Sabatier reaction using hydrogen and CO_2; carbon monoxide is produced from reverse water gas shift (RWGS); and methanol is produced from hydrogenation except for pathway 8 (methanol from photocatalytic reduction). For this pathway, we assume methanol is also produced from photocatalytic reduction using the inventory data for pathway 1, which is from the same study.[24]

Technology Readiness Level (TRL) is an indicator that summarizes information on technological maturity into a single value.[47] The scale has three phases with nine levels, spanning from a basic idea (TRL 1) to a technology demonstration (TRL 9).[48] CCU pathways are at very different TRLs so the timing for them to progress to demonstration varies. Studies indicated that it takes 10–15 years and 20–30 years, respectively, for CCU pathways to move from lab scale (TRL 4–5) and research phase (TRL 1–3) to commercial deployment.[15,49] Based on the TRL of each CCU pathway in 2020 and the aforementioned assumptions, we estimate the earliest available year for the deployment of all pathways, represented in the circles with varying shades of blue in Fig. 1. Specifically, pathways with TRL greater than 7 (in 2020) are assumed to be available in 2020; those at TRL 6 in 2030; TRL 4–5 in 2040 and TRL <3 in 2050. However, we note there are large uncertainties around the pace of technology development and these associated deployment timelines; they are provided for context only and are not a direct input into the model calculations. While there are inherent limitations in developing and evaluating life cycle inventories for emerging technologies[50] especially those at different TRLs, we adopt a 'best available estimate' approach for each pathway; this enables us to focus on our study objective regarding the impact of background systems on life cycle GHG intensity, while acknowledging the large uncertainties surrounding these estimates for emerging technologies.

Among the investigated CCU pathways, differences in catalysts, reactor design, and other underlying modelling assumptions may lead to substantial variations in published inventory data, making it challenging to harmonize reported values into a reliable range for a given pathway. Prior work has shown that results from different studies for a same pathway must be interpreted within the context of each model's specific assumptions.[51] Therefore, we adopt point estimates from individual studies as internally coherent representations of each pathway. This approach allows us to focus on how background systems influence the GHG emissions of these representative pathways, rather than attempting to characterize the full landscape of all possible process designs.

2.4 Incumbent pathway module

The Incumbent pathway module includes the most common production methods used in Canada for the investigated chemicals and fuels. Most incumbents are fossil-based, while ethanol production in Canada primarily uses corn and wheat feedstocks.[52] This module includes one incumbent pathway for each product, resulting in 13 incumbent pathways (see Table S2). Although there are additional relevant incumbent pathways (*e.g.*, ethanol can partially replace gasoline,[53] DME can potentially replace diesel[54]), we restrict our comparison to the nearest equivalent fossil-based product to avoid complicating the comparisons.

The 13 final products from the incumbent pathways are identical to the products from the comparable CCU pathways. Consistent with previous literature, we assume the final products with the same chemical structure and composition produced from the incumbent pathways could be avoided if CCU pathways are deployed.[7] In some cases, the final products from the CCU pathway and the identified incumbent pathway are different, making the two systems incomparable. In those cases, we adjust the outputs to ensure the final products from the two systems are identical. For example, when we evaluate the syngas production pathways (*i.e.*, SMR or dry reforming [DRM]), we applied system expansion to add additional hydrogen to the DRM pathways to ensure the ratios of hydrogen and carbon monoxide in the final products from the two pathways are 3 to 1 (see Section S1.4 for further details).

2.5 Background system

The level of detail of the background system can vary from a black-box perspective, where only the main inputs and outputs are defined, to a full-scale technology characterization, including all underlying parameters.[55] The black-box perspective is used in this work to represent the common parameters (*i.e.*, electricity, heat and hydrogen) that affect the GHG intensities of most CCU pathways. Previous literature primarily collect background system data from LCI databases (*e.g.*, Ecoinvent and GaBi).[18,56] However, those datasets may not adequately capture changes in background systems over time within the Canadian context. To address these issues, we explore 12 harmonized background system scenarios to model potential trajectories of the GHG intensity of electricity, heat and hydrogen from 2020 to 2050 in Canada and evaluate the emissions intensities of the 20 CCU pathways under those 12 scenarios (summarized in Table 1).

For electricity, we consider two scenarios from Canadian Energy Regulator's Canada's Energy Future 2023 report: the Current Policy Scenario and the Global Net-Zero Scenario (NZE).[57] These scenarios differ in the projected primary fuel sources for Canada's electricity generation from 2020 to 2050,[57] with the corresponding generation fuels and technologies in 2020 and 2050 highlighted in Fig. 2A. Due to the lack of publicly available life cycle emission intensities for each fuel source from Canada Energy Regulator, we use its data only for the projected fuel mix and combine them with median GHG intensity for each electricity generation source from National Renewable Energy Laboratory (NREL)[58] to estimate Canada's electricity GHG intensity from 2020 to 2050 under both scenarios, which is shown in Fig. 2B. This approach may result in some minor variations from the emission estimates modeled by Canadian Energy Regulator but ensures data source consistency across electricity generation technologies within our analysis given the data limitation.

Table 1 12 Harmonized background system scenarios[a]

	Electricity		Hydrogen			Heat	
	Current policy (C)	NZE policy (Z)	Market share (M)	SMR (S)	Alkaline electrolysis (A)	Natural gas boiler (N)	Electric boiler (E)
S1 (C, M, N)	√		√			√	
S2 (C, M, E)	√		√				√
S3 (C, S, N)	√			√		√	
S4 (C, S, E)	√			√			√
S5 (C, A, N)	√				√	√	
S6 (C, A, E)	√				√		√
S7 (Z, M, N)		√	√			√	
S8 (Z, M, E)		√	√				√
S9 (Z, S, N)		√		√		√	
S10 (Z, S, E)		√		√			√
S11 (Z, A, N)		√			√	√	
S12 (Z, A, E)		√			√		√

[a] Each scenario contains three letters within brackets. The first letter represents the electricity scenario, with C and Z denoting electricity intensity in current policy and net zero emission scenarios.[57] The second letter indicates the hydrogen generation method, M represents hydrogen purchased from the market, S represents hydrogen generated by steam methane reforming, and A represents hydrogen produced from alkaline electrolysis. The third letter indicates the heat generation scenario, where N represents the natural gas boiler, and E represents the electric boiler.

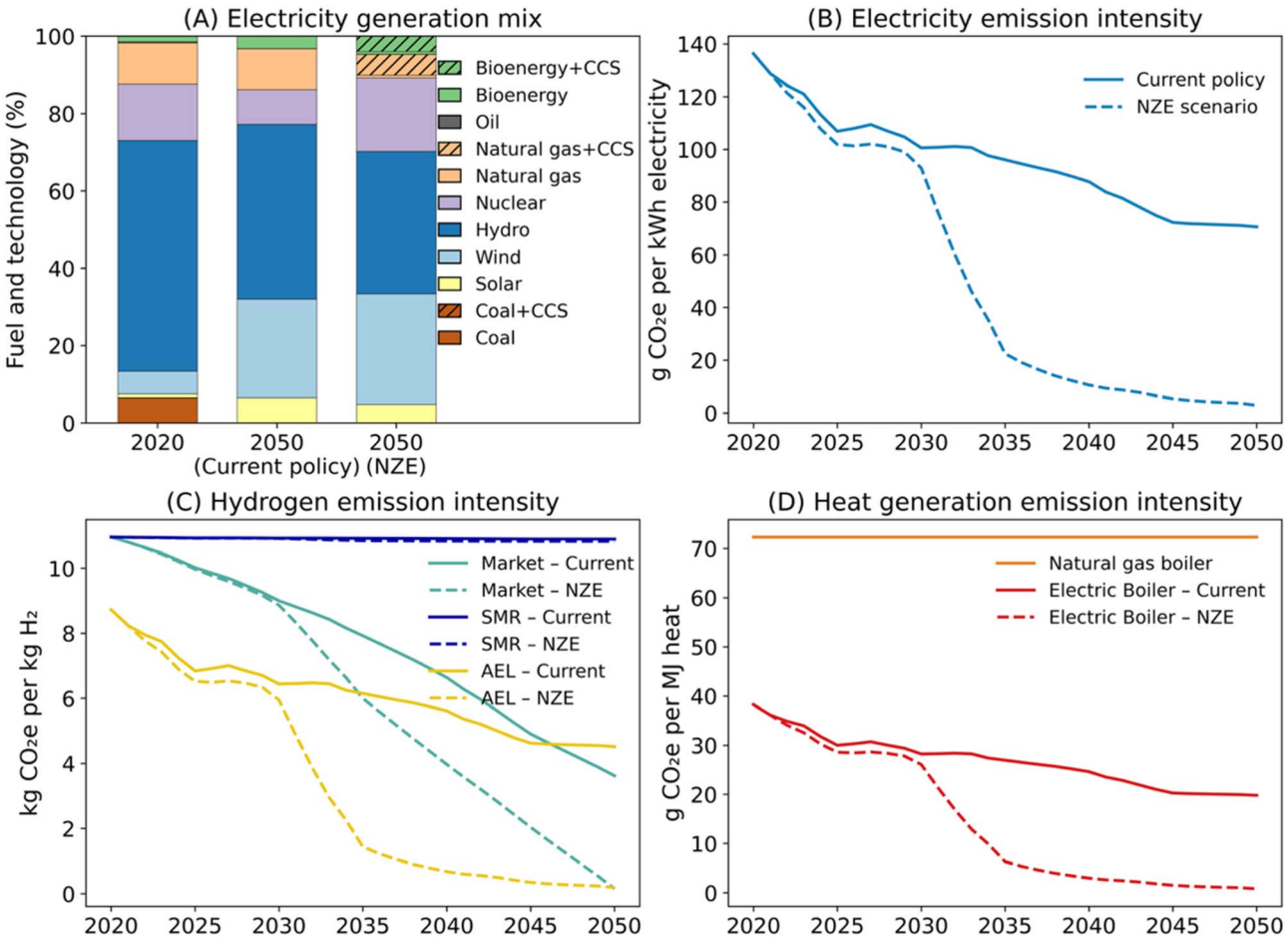

Fig. 2 Electricity generation mix and emission intensity trajectories for electricity, hydrogen, and heat under different scenarios. Panel (A) shows the share of electricity generation by fuel and technology in 2020 and under two 2050 scenarios: the current policy electricity scenario and the net zero emissions (NZE) scenario. Panel (B) presents the trajectory of electricity emission intensity in Canada from 2020 to 2050. Panel (C) shows hydrogen production emission intensity for market-average, steam-methane reforming (SMR), and alkaline electrolysis (AEL) pathways. Panel (D) illustrates heat generation emission intensity for natural gas and electric boilers. In Panels (B)–(D), solid lines represent the current policy scenario, and dashed lines represent the NZE scenario.

For hydrogen, we consider three scenarios. The first scenario assumes hydrogen is produced on-site from SMR, which is the dominant hydrogen production method in Canada.[59] To produce 1 kg of hydrogen from SMR in Alberta, 11.35 kg CO_2e of GHG will be emitted, with 0.52 kg CO_2e of emissions coming from the 0.96 kWh of electricity using the Alberta grid and 10.82 kg of emissions coming from natural gas emissions.[60] In our model, we replace the fixed Alberta electricity GHG intensity from that study with a dynamic Canadian average electricity GHG intensity, allowing us to estimate the emissions of SMR-based hydrogen production from 2020 to 2050 under different electricity scenarios. The second scenario assumes hydrogen is produced from alkaline electrolysis (AEL) with an efficiency of 64 kWh per kg H_2,[61] which is the most mature water electrolysis technology to produce hydrogen.[62] The last scenario considers a dynamic mix of hydrogen production methods from 2020 to 2050, based on US DOE projections that the dominant SMR-based hydrogen production will gradually be replaced by various water electrolysis technologies.[61] Given the changing market shares of hydrogen production methods over time, the efficiency variations of different electrolyzers, and the changing electricity GHG intensity over time, we estimate the emission factors of hydrogen production from 2020 to 2050 shown in Fig. 2C.

For heat generation, we consider two industrial boiler scenarios. The first is a natural gas boiler, representing the status quo technology.[48] The emission factor is sourced from Ecoinvent for Quebec region in Canada.[39] As a more sustainable alternative, we also assess an electric boiler, which can meet the high-temperature process heat demands of the chemical reactions examined in this study.[63] The emissions from electric boilers are determined by the changing greenhouse gas intensity of electricity generation in Canada over time shown in Fig. 2D. Although options exist for other renewable or low-emission fuel sources (*e.g.*, renewable natural gas)[63] there remain controversies over their availability and GHG accounting[64,65] and their inclusion would substantially expand the background system permutations beyond what required for this study. Moreover, some renewable fuels cannot achieve the high temperatures needed for certain industrial processes,[63] further limiting their applicability in this context.

The electricity, hydrogen and heat generation pathways are combined into 12 harmonized background system scenarios, summarized in Table 1 with additional details in S1.3.

2.6 Calculation of cradle-to-gate emissions of CCU pathways

Eqn (1) summarizes the calculation of cradle-to-gate emissions of a CCU pathway ($E_{\text{net},p,t}$), which depends on the emissions from the CO_2 capture process ($E_{\text{CO}_2\text{capture},p,t}$), conversion process ($E_{\text{conversion},p,t}$), the amount of utilized CO_2 ($E_{\text{utilizedCO}_2,t}$), and the avoided emissions that would have been generated from producing the identical product *via* incumbent pathways ($E_{\text{avoided incumbent},p,i,t}$). The detailed calculation for each component in eqn (1) is given in the eqn (2)–(4) in S1.7 in SI. Note all emissions are harmonized to the functional unit of 1 kg of utilized CO_2 to allow us to compare all investigated CO_2 pathways.

$$E_{\text{net},p,t} = E_{\text{CO}_2\text{capture},p,t} + E_{\text{conversion},p,t} - 1 - E_{\text{avoided incumbent},p,i,t} \quad (1)$$

where: $E_{\text{net},p,t}$ represents the net GHG emissions of CCU pathway p in year t (kg CO_2e per kg CO_2 utilized) $E_{\text{CO}_2\text{capture},p,t}$ represents the emissions from capturing CO_2 for pathway p in year t (kg CO_2e per kg CO_2 utilized). $E_{\text{conversion},p,t}$ represents the conversion emissions from utilizing 1 kg of CO_2 to produce a chemical *via* pathway p in year t (kg CO_2e per kg CO_2 utilized). 1 represents the credit for the uptake of 1 kg CO_2 per functional unit. $E_{\text{avoided incumbent},p,i,t}$ represents the avoided emission from incumbent pathway i that could be replaced by CCU pathway p to produce the same final product (kg CO_2e per kg CO_2 utilized).

3. Results and discussion

3.1 CCU, incumbent, and net GHG emission intensity ranges under the background scenarios

We calculate the emissions intensity of all pathways for each year from 2020 to 2050 under the 12 background system scenarios (the full set of results are in the SI-Excel). Here, we focus on the results for 2020 and 2050 to provide snapshots in the short and long term shown in Fig. 3. The emissions for 19 out of the 20 pathways are presented in Fig. 3, while the emissions for DMC from the electrochemical pathway are shown separately in Fig. S2. This is for readability, given that the DMC pathway has considerably higher emissions than the other pathways. Fig. 3 contains 6 subplots, each with 19 boxplots, which reflect the GHG intensity range for each pathway (Fig. 1) across the 12 background system scenarios (Table 1). Each boxplot reflects a specific pathway, and individual dots within a boxplot represent results for single scenarios. Pathways are categorized into four groups, represented by varying shades of blue, based on their TRL and the resulting estimated year for their available deployment. Although not all pathways were available in 2020, their emissions under the 2020 background system are estimated to determine whether these pathways would have had greater emissions than currently available incumbent pathways if they had been available in 2020. Panels A1 and A2 show the absolute emissions of the CCU pathways for 2020 and 2050 background systems, respectively. A positive value indicates that the production process generates higher emissions than the amount of utilized CO_2, whereas a negative value indicates that the emissions are lower than the utilized CO_2. B1 and B2 show the avoided emissions resulting from replacing incumbents. C1 and C2 show the net emissions of the CCU pathways. A positive value indicates that the emissions from the CCU pathway are higher than those from the incumbent pathway and thus continuing with the deployment of an incumbent pathway while changing the background system is preferred. Conversely, a negative value means the emissions from the CCU pathways are lower than those from the incumbent pathway, making the CCU pathway a more desirable option for producing the product, provided that the pathway performs as currently predicted.

3.1.1 CCU pathway results: under 2020 background systems 4 pathways sequester more CO_2 than they release; under 2050 background systems 19 out of 20 pathways do so.

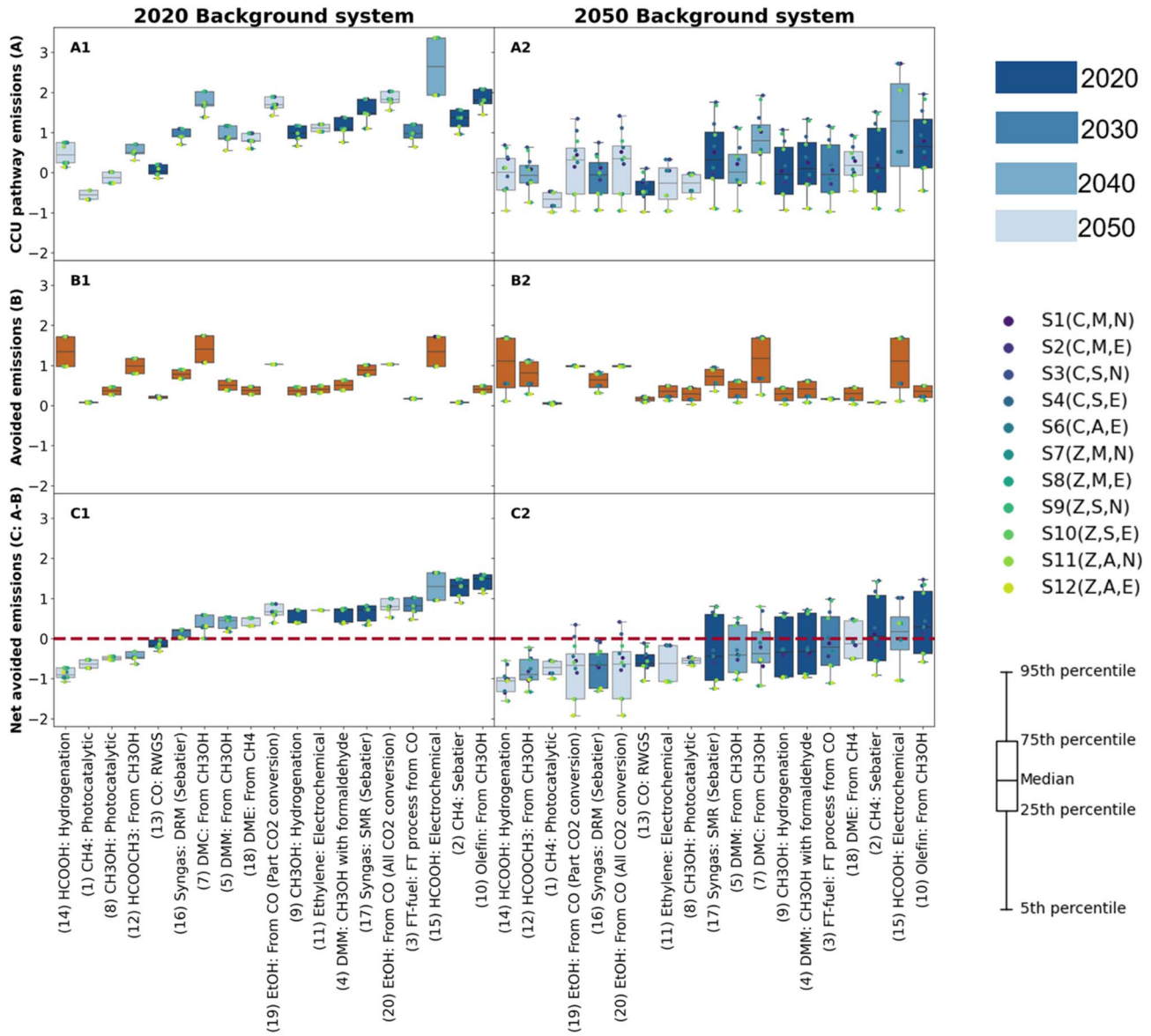

Fig. 3 Ranges of emissions of investigated CCU pathways from utilizing 1 kg of CO_2 in 2020 and 2050 (kg CO_2e per kg utilized CO_2). Pathways are as described and numbered in Fig. 1 and Table S1. Results for DMC from the electrochemical pathway are shown in Fig. S2. Panels A1 and A2 represent the absolute emissions of CCU pathways with 2020 and 2050 background systems, respectively. B1 and B2 represent the avoided emissions from the replaced incumbents in 2020 and 2050 background systems, respectively. C1 and C2 represent net emissions of CCU pathways in 2020 and 2050 background systems, respectively. Pathways are shown from left to right in the panels based on their median net emissions in 2020 or 2050. Boxplots represent the distribution of results across 12 background scenarios, each consisting of varying electricity carbon intensity, hydrogen and heat generation methods. Individual dots in a box represent results for single scenarios. Wider bars indicate greater variances among scenarios, highlighting the impact of the background system on the pathways. Numerical results underlying this figure are available in SI-Excel.

According to A1 in Fig. 3 and S2, with the 2020 background system scenarios, 4 of the 20 pathways could achieve negative cradle-to-gate emissions (including credits for utilized CO_2) in optimistic scenarios where all heat inputs are electrified. Most of the remaining pathways have emissions ranging from 0 to 2 kg CO_2e per kg of CO_2 utilized, except for 2 electrochemical pathways producing formic acid and DMC, which have up to 3.3 kg CO_2e and 54 kg CO_2e of emissions, respectively. The higher emissions associated with the 2 electrochemical pathways can be attributed to the considerable energy demand for distillation of the low-concentration formic acid (4.5 wt%) and DMC (0.9 wt%) from the electrochemical reactor. Specifically, the source studies estimate 150 MJ of heat is needed to distill 1 kg of formic acid,[66] and 1324 MJ of energy (497 MJ of heat energy and 827 MJ of electricity) to distill 1 kg of DMC.[6] Additionally, the very low reaction yield (0.7% relative to the methanol input) for the modeled DMC pathway further contributes to the high energy demand in the separation process.[6]

For the 2050 background system (A2 in Fig. 3), all CCU pathways are projected to have lower emissions than with the

2020 background system and 19 out of 20 pathways could potentially have negative emissions in certain scenarios, meaning their cradle-to-gate emissions are lower than the utilized CO_2. DMC from the electrochemical pathway is the only exception, which has positive emissions in all scenarios. Nevertheless, emissions for this pathway may be decreased by up to 99%, reaching 0.4 kg CO_2e per kg of utilized CO_2 in scenarios S8 and S12. In these scenarios, the carbon intensity of electricity is projected to be about 3 g CO_2e per kWh. This very low value is partly driven by the inclusion of negative emissions associated with bioenergy with carbon capture and storage (BECCS), which supplies approximately 4% of total electricity generation in the NZE scenario. Hydrogen is from water electrolysis technologies using this low GHG-intensity electricity and heat is generated using electric boilers that also utilize the same low GHG-intensity electricity.

3.1.2 Incumbent pathway results also sensitive to background systems. The emissions of the incumbents for the 20 investigated pathways are displayed in B1 and B2 in Fig. 3 and S2. As shown by the range across scenarios in B1, the avoided emissions from the incumbent pathways are influenced by the background system to varying extents. Formic acid from carbon monoxide and DMC from the Eni process have the greatest variance, while FT fuel from crude oil and methane from natural gas recovery have the smallest variance among scenarios, due to the fossil input and high fixed emissions associated with these processes. This finding has been overlooked in the literature, which usually compared the emissions of CCU pathways in different scenarios with a constant value for incumbent pathways.[4,15,41] However, it should be noted that all the investigated incumbent pathways require electricity, and 18 of 20 pathways also require thermal energy. Once the electricity and heat sources are decarbonized, the emissions of incumbent pathways can be substantially reduced. Therefore, using a constant background system or a fixed value to represent the emissions of incumbent pathways is insufficient.

3.1.3 Net emissions results: CCU pathways are not guaranteed to reduce emissions, but most offer mitigation potential in a world with lower GHG intensity background systems. A low carbon intensity background system is crucial for CCU pathways to achieve lower emissions than their incumbents. With the 2020 background system, only 5 pathways might have net avoided emissions (*i.e.*, lower emissions than the incumbent). Fig. 3, Panel C1 shows that the two photochemical CCU pathways to produce methane (pathway 1) and methanol (pathway 8) have lower emissions than their incumbents, thus net avoided emissions in the 2020 background system. This is primarily because these pathways use semiconductors that rely on sunlight to facilitate the reaction, eliminating the need for direct electricity use during the process. Only a small amount of electricity is required for the upstream water desalination process. Additionally, a small amount of heat is necessary for the methane drying process, which is provided by methane from the photocatalytic reactor and constitutes just 1% of the total methane produced.[24] Switching from the current production methods to the CCU pathways using photocatalysis is a favorable choice in terms of emission reduction, even with the 2020 background system. In addition to the two photochemical pathways, formic acid from hydrogenation (pathway 14), methyl formate from CO_2-based methanol (pathway 12), and syngas from RWGS (pathway 13) also have net avoided emissions in all scenarios in the 2020 background system. This is because the foreground system of these pathways uses much less energy than the foreground system of the incumbent pathways. For the remaining CCU pathways that have higher emissions than incumbents in all 2020 background system scenarios, continuing with the deployment of incumbent pathways while changing the background system is preferred – at least in the absence of other process improvements to the CCU foreground systems.

Shifting from 2020 to 2050 background system, the number of pathways that might have net avoided emissions increases from 5 to 19. All pathways except DMC from the electrochemical pathway have the potential for lower emissions than their incumbents. Also, pathways that can achieve net avoided emissions under both background systems show greater emission reduction potential in the 2050 system. For example, pathway 14's lowest net emissions in the 2020 and 2050 background systems are −1 and −1.6 kg CO_2e per kg CO_2 utilized, respectively. This suggests that the background system has a considerable impact on all investigated pathways in the long run. In 2050, if electricity with low carbon intensity were guaranteed, hydrogen could be produced through electrolysis, and the heat generation method could be replaced by an electric boiler (or other low carbon source), most pathways could achieve lower GHG emissions than their incumbents.

3.2 Emission contribution and impact of each background system parameter

To understand how individual background system parameters affect pathway emissions, we explored four scenarios. Results are shown in Fig. 4 for 19 pathways and in Fig. S3 for the electrochemical DMC pathway (separated for readability). We use the 2020 background system scenario 3 as our baseline scenario (black dots), representing near-current conditions: electricity emission factor is from 2020 grid mix, hydrogen is sourced from SMR, and heat is fueled by natural gas. The stacked bars in Fig. 4 show how different life cycle components contribute to baseline emissions. The remaining three scenarios illustrate the effects of progressively changing individual parameters: changing electricity only (orange dots), changing electricity and hydrogen (blue dots), and changing electricity, hydrogen, and heat (red dots). The contribution plots for these three scenarios are shown in Fig. S4.

3.2.1 Electrochemical pathways require very low carbon electricity. The five electrochemical pathways consume more electricity than other pathways given the same amount of CO_2 feedstock. Through using 1 kg of CO_2, 13 kWh of electricity will be utilized to produce 0.32 kg of ethylene, 9 kWh of electricity will be utilized to produce 1.05 kg of formic acid, and 57 kWh of electricity is needed to produce 0.68 kg of DMC. After these three electrochemical pathways, the two electrochemical ethanol production pathways also consume considerable

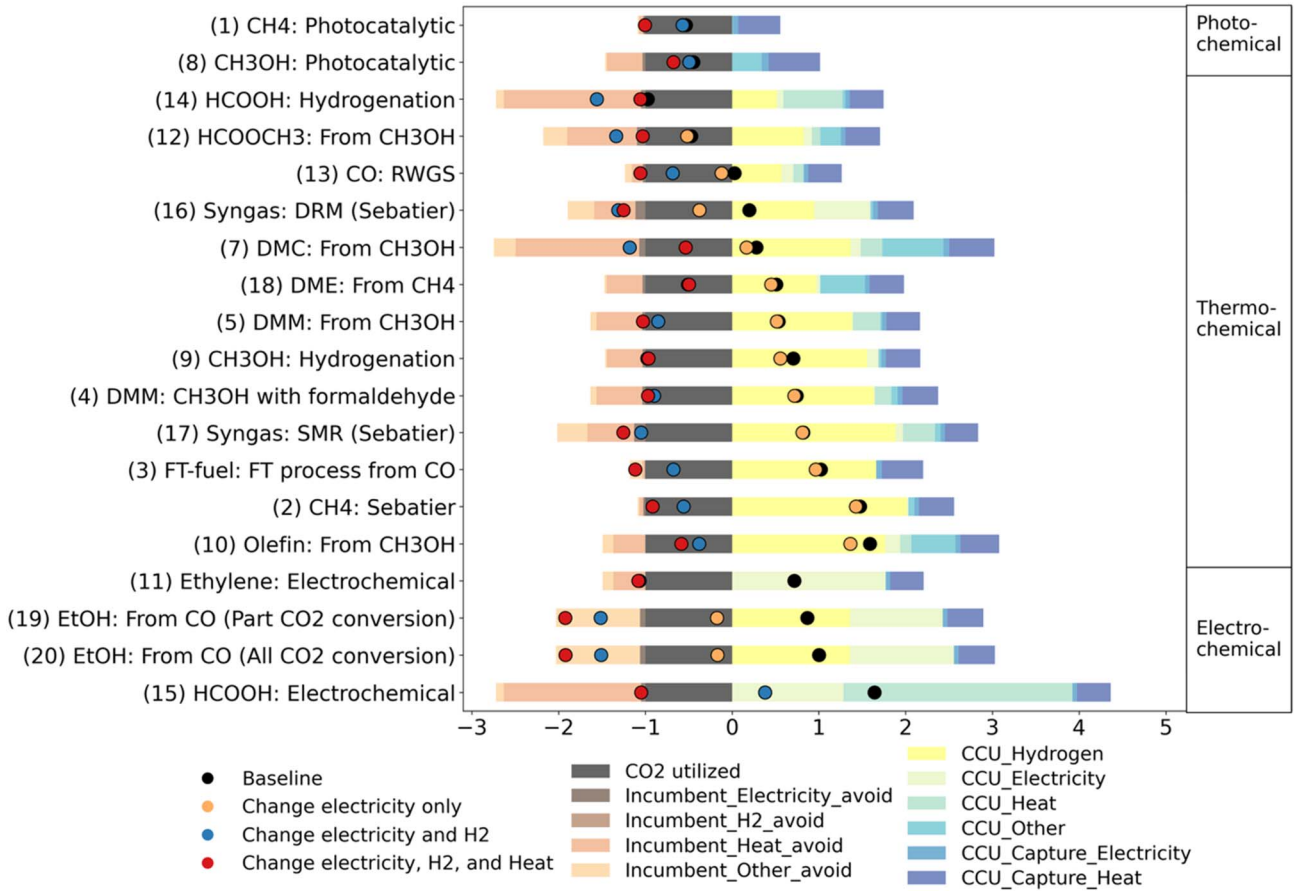

Fig. 4 Contribution of different stages to the net emissions of CCU pathways in the baseline scenario and the net emissions in four scenarios. Results for DMC from the electrochemical pathway are excluded for readability reasons and are shown in Fig. S3. The contributors to the emissions of the CCU pathways (shown on the right side of the zero line), include hydrogen production, electricity generation, heat generation, and other emissions (*i.e.*, fixed emissions from feedstock that are not affected by the background system and air emissions from the production process), and the electricity and heat used for CO_2 capture. The emissions from the CCU pathways are offset by the captured CO_2 and emissions from the heat, electricity, and hydrogen, as well as others that are required for producing the same amount of identical chemicals from incumbent pathways (shown on the left side of the zero line). The baseline scenario (represented by black dots) shows the net emissions of the CCU pathways if the 2020 background system remains unchanged. In the "Change electricity only" scenario (represented by orange dots), the net emissions of CCU pathways were examined under reduced electricity carbon intensity. The "Change electricity and H_2" scenario (represented by blue dots) shows the net emissions of CCU pathways if hydrogen is generated from water electrolysis using low-carbon intensity electricity. Lastly, the "Change electricity, H_2, and Heat" scenario (represented by red dots) shows the net emissions of CCU pathways if heat is generated from electric boilers using low electricity intensity. In some cases, fewer than 4 dots are visible because certain scenario results overlap. For example, for pathway 11, the "Change electricity only" and "Change electricity and H_2" scenarios yield identical results because both CCU and incumbent pathways do not need hydrogen, so the blue dot overlaps the orange dot. Within each group (photochemical, thermochemical, and electrochemical), pathways are ordered by their baseline net emissions from highest to lowest.

electricity as they require a CO_2 electrolyzer to convert CO_2 to carbon monoxide. In the baseline scenario, the net emissions of these five electrochemical conversion pathways are positive, which is notable considering Canada's already relatively low GHG intensity for electricity production in 2020 (~137 g CO_2e per kWh). After changing the electricity to the 2050 level in the NZE scenario, three pathways have net avoided emissions (pathways 11, 19, 20). The other two pathways (6 and 15) that still have positive net emissions have considerably lower emissions compared to the baseline scenario. The emissions of DMC and formic acid decreased by 12% from 53.1 kg CO_2e to 46.9 kg CO_2e and 75% from 1.6 kg CO_2e to 0.4 kg CO_2e, respectively. Since these pathways are sensitive to electricity carbon intensity, when these pathways are deployed, low GHG-intensity electricity needs to be guaranteed to ensure low emissions of these pathways.

3.2.2 Thermochemical pathways' GHG intensity are primarily sensitive to hydrogen GHG intensity. In contrast to the electrochemical pathways where electricity is a key contributor to GHG emissions, hydrogen production is the greatest contributor to the thermochemical pathways' GHG emissions in the baseline scenario. As shown by the orange dots (Fig. 4), with only changes in electricity GHG intensity, their emissions only slightly decrease. However, after changing the hydrogen generation method from SMR to alkaline electrolysis (with an efficiency of 64 kWh per kg H_2), all thermochemical pathways are projected to have lower emissions than their incumbents. It should be noted that the emissions from

hydrogen tie closely with the electricity carbon intensity when hydrogen is produced from electrolysis. When the electricity carbon intensity stays at the 2020 baseline scenario value (137 g CO_2e per kWh), only 4 of 13 thermochemical pathways are projected to have lower emissions than their incumbents when changing the hydrogen generation option. But when the electricity carbon intensity is 2.9 g CO_2e per kWh, all 13 thermochemical pathways are projected to have lower emissions than their incumbents. This suggests that for thermochemical pathways, low-carbon hydrogen is important.

3.2.3 Photochemical pathways are the least sensitive to background system changes. In contrast to the thermochemical pathways, which are sensitive to the carbon intensities of electricity and hydrogen, the background system has a smaller impact on the two photochemical pathways. These carbon conversion technologies do not need heat, hydrogen, and electricity directly because their reactions need sunlight, water, and dye-sensitized semiconductors. The electricity used to desalinate water is included, which is consistent with the original study.[24] But the environmental impact of manufacturing semiconductors is not considered because our study excludes the infrastructure. Note that the materials that are used to manufacture semiconductors, such as glass and concrete are carbon intensive. If we consider the emissions from making the reactor, the emissions of these pathways would be much higher. As these pathways do not require direct electricity but instead sunlight and a wide reactor area, southern Alberta and Saskatchewan can be good places to deploy these photochemical pathways because of higher solar insolation combined with relatively carbon-intensive electricity grids in these two provinces compared to other provinces in Canada.

3.2.4 The combined effect of background system changes is substantial, but requires fair comparisons against incumbent pathways. Comparing the results of the four scenarios, for most pathways, the net emissions would be the lowest in the "Change electricity, H_2, and Heat" scenario, shown as red dots. There are a few exceptions where the net emissions may increase after the heat generation method switches to the electric boiler (*e.g.*, pathway 14 formic acid from hydrogenation). This does not mean the emissions of those CCU pathways increase after switching to an electric boiler. Instead, it means the emission reductions from substituting the incumbent pathways with the CCU pathways are smaller because heat generation has a more significant impact on the incumbent pathways than CCU pathways.

3.3 Resources needed for CCU pathways

As discussed in Section 3.1.3, 19 out of 20 pathways may have lower GHG emissions than their incumbents under the 2050 background system when the electricity carbon intensity is low, hydrogen is produced from water electrolysis, and heat is generated from electric boilers. This may require a significant increase in the amounts of hydrogen, heat, and electricity when CCU pathways replace incumbent pathways. To quantify these resource demands, we calculate the product quantity needed to achieve 1 kg CO_2e net avoided emission reduction for each of the 19 pathways across 12 scenarios (see Section 3.1.3). We then calculate the additional resource demand for producing the calculated quantity of product in different scenarios, based on the net difference in electricity, hydrogen, and heat demand between CCU and incumbent pathways for producing 1 kg of product. We then identify which background scenario results in the minimum additional electricity, hydrogen, and heat needed to achieve a 1 kg CO_2e emission reduction for each product and display the results in Fig. 5. We find that, to achieve 1 kg of net avoided emissions, most pathways require 0–20 kWh of additional electricity, 0–1 kg of additional hydrogen, and 0–20 MJ of additional heat. Transitioning from an incumbent pathway to a CCU pathway may not always require additional heat. As shown in Fig. 5, 6 of 19 pathways result in a reduction in heat demand to achieve emissions reduction.

Electricity is the most important background system parameter, not only because almost all pathways need it directly during the conversion process, but also because it affects other background system parameters. 1 MWh of electricity is required to produce 15–20 kg of hydrogen through AEL.[9,61] Switching from fuel-based boilers to electric boilers results in higher electricity load at industrial plants.[67–69] We also find that if we fully electrify the hydrogen and heat production, pathway 10 (olefin from methanol) has the highest electricity demand among all pathways and the majority of pathways would require 1 to 20 kWh of additional electricity for every 1 kg of net avoided emissions as shown in Fig. S5.

3.4 Uncertainty of future incumbent and CCU pathways

There are uncertainties associated with the incumbent pathways, as pathways heavily deployed today may not be relevant incumbent pathways in the future.[7] CCS is a widely discussed strategy to reduce the GHG emissions of incumbent pathways.[70] Previous studies found that after installing a carbon capture unit, the emissions from bio-ethanol,[71] fossil-based methanol[72] and coal-based olefin[73] would be reduced by 88%, 96%, and 62%, respectively. We take the results from the three studies to evaluate whether the CCU production of these products would still have lower emissions than the incumbents when CCS is deployed. Overall, with the 2020 background system, CCS is found to be a preferred option over CCU in all scenarios. With the 2050 background system, whether CCS would be the lowest-GHG intensity pathway depends on the specific background system scenario. For example, in scenario 12 (net-zero scenarios for electricity, alkaline electrolysis for hydrogen, electric boilers for heat), all four pathways that considered CCS show net avoided emissions, indicating that utilizing CCU is preferable to implementing CCS on incumbent pathways (see Fig. S6).

There are also substantial uncertainties associated with the CCU pathways arising from the incomplete data and methodological challenges associated with modeling low TRL technologies.[74] Foreground process improvements or novel CCU pathways toward producing the same product could further alter the favorability of the modeled processes. Technological innovations in incumbent foreground systems, including reactor electrification *via* plasma, microwave, or inductive heating,[75,76] introduce additional changes in the emission

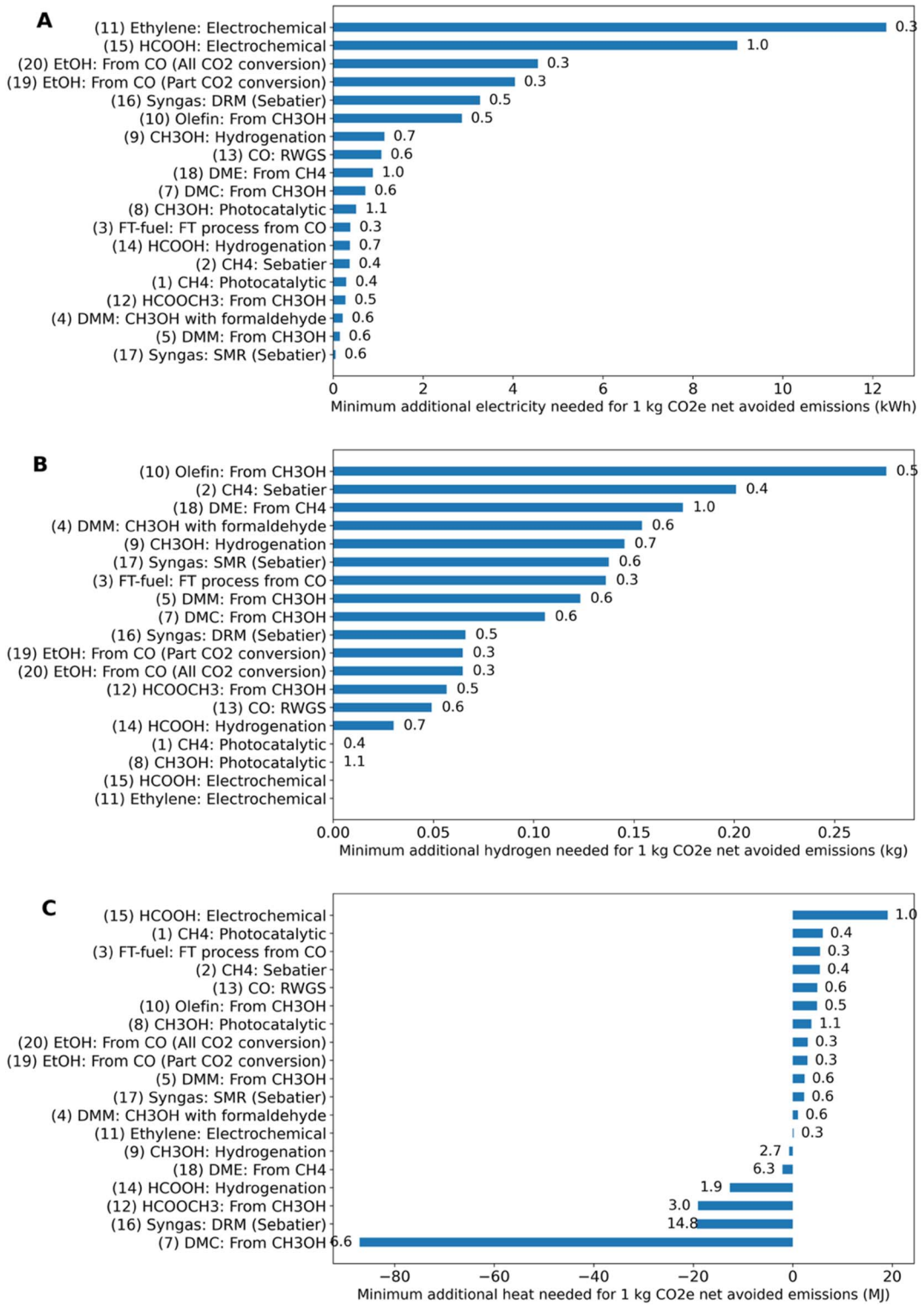

Fig. 5 Minimum additional demands for electricity (A), hydrogen (B), and heat (C) for 1 kg CO_2e of net avoided emissions for each of the CCU pathways from across the 2050 background system scenarios. The numbers beside the bar show the quantity (in kg) of the corresponding final product required. In subplot B, pathways 11 and 15 do not require hydrogen as a feedstock in incumbent or CCU pathways, so there is no effect on hydrogen demand.

estimates of the incumbent pathway for fuel and chemicals production.[77–81] In addition, we acknowledge that input data for the investigated technologies may vary across sources. Using DAC as an example, our sensitivity analysis shows that variations in DAC energy demand can alter the number of CCU pathways that achieve lower emissions than their incumbent

pathways. The impact of this variation is more pronounced under the baseline background system scenario, where energy and material supply remain carbon-intensive. As the energy system decarbonizes, the influence of DAC input assumptions diminishes because the overall carbon intensity of the background system becomes smaller (see Fig. S7).

Beyond DAC, inputs for CCU pathways may also vary widely because of differing underlying modelling assumptions across studies, making it difficult to harmonize reported values for the same pathway. For example, our photocatalytic methanol pathway is based on Trudewind *et al.*,[24] which remains widely cited in recent studies.[82–84] Some recent photocatalytic work employs different catalysts (*e.g.*, Ni/CeO_2 (ref. 85) and graphitic carbon nitride[86]) and distinct reactor configurations.[87] Because catalyst composition and reactor configuration strongly influence energy requirements, these data are not directly comparable to the data from Trudewind *et al.* and may not reliably define sensitivity ranges in a straightforward way. Similarly, while many studies investigate the same one-step electrochemical CO_2-to-ethylene reaction and the values used in our analysis fall within the broad literature range (see Table S4), electrolyzer design, faradaic efficiency, cell voltage, and other underlying modelling assumptions differ substantially across studies. For example, Kim and Benavides[51] shows that increasing faradaic efficiency from 40% to 80% for the single-step membrane electrode assembly pathway while holding other parameters constant decreases electricity use from 110 kWh to 57 kWh per kg of ethylene. Together, these differences show that electricity requirements and the resulting GHG emissions depend strongly on study-specific modelling assumptions (see SI Section 1.9 for additional details and discussion). Given this substantial variability, our results should be interpreted as directional trends rather than precise forecasts of future technological performance. This consideration also applies to other low-TRL CCU pathways whose projected GHG emissions depend heavily on underlying modelling assumptions and that face similar challenges in harmonizing and comparing data.

The economic feasibility of CCU deployment also remains uncertain. Recent studies report that the current cost of large-scale DAC systems ranges from USD 80 to 1133 per t_{CO_2} (ref. 88 and 89) while electrolytic hydrogen production typically ranges from USD 2 to 6 per kg H_2.[90,91] These upstream costs translate directly into higher production costs for CO_2-derived fuels and chemicals. For example, the production cost of renewable e-methanol using DAC-derived CO_2 is currently estimated at USD 1200–2400 per tonne, compared with USD 100–250 per tonne for fossil methanol, meaning present costs can be several times higher.[92] Future reductions in these costs will be critical for determining the practical deployment potential of CCU pathways. Additional information about technical and logistical feasibility of the projected pathways is also required prior to making firm recommendations.

4. Conclusion

In this study, we assess the change in GHG emissions intensity of 20 CCU chemical and fuel pathways and their incumbents from 2020 to 2050 while considering the maturity of each pathway and changes in the background system over time. Our results show that GHG emissions for most CCU pathways vary greatly based on the background system, with electricity GHG intensity being the most impactful factor. To minimize GHG emissions, low GHG electricity intensity is crucial but does not guarantee lower emissions compared to incumbent pathways. The choice of buying merchant hydrogen or producing it onsite, the market penetration of water electrolysis technologies, and the use of electric boilers also play major roles in reducing GHG emissions in industrial plants.

Second, this study highlights that most incumbent pathways' GHG intensities are also sensitive to background system changes because the investigated incumbent pathways need electricity, and most of them require heat. Once the electricity and heat sources are decarbonized, the emissions of incumbent pathways can be substantially reduced. Therefore, using a constant background system or a fixed value to represent the emissions of incumbent pathways is insufficient. To ensure fair comparisons of the emissions of CCU pathways and incumbent pathways, it is crucial to consider the impact of the background system on both types of pathways.

Our study also highlights the need to consider the technological maturity of different pathways when identifying those most promising to assist with near-to-medium term GHG mitigation efforts. Although we find five pathways can have lower emissions than their incumbents in all harmonized 2020 background system scenarios, only carbon monoxide *via* RWGS is a mature technology and could be deployed at a demonstration scale; the other pathways are estimated to be available in 2040 or 2050 based on their TRLs. Note that while TRL is used as a framework to provide the best available estimate for each pathway in this work, we acknowledge the large uncertainties surrounding these estimates, particularly that different technologies may not progress at the same pace.[93] We also note that these deployment assumptions do not affect the quantitative LCA results presented in this study, but are simply provided for context around how soon different technologies might be available.

Lastly, our analysis shows that the net GHG emissions of all investigated pathways, except DMC from the electrochemical pathway, can be negative under highly optimistic 2050 background system scenarios in which the electricity carbon intensity is low, hydrogen is produced from water electrolysis, and heat is generated from electric boilers. However, this calls for considerable increases in demand for low-carbon electricity and electrolytic hydrogen if CCU pathways were to replace incumbent pathways, highlighting the importance of further developing renewable energy to support the large-scale implementation of CCU technologies.

Author contributions

Mengqing Kan: conceptualization, methodology, visualization, formal analysis, writing – original draft. Sylvia Sleep: conceptualization, methodology, validation, writing – review & editing, supervision. Heather L. MacLean: conceptualization, methodology, validation, writing – review & editing, supervision. I.

Daniel Posen: conceptualization, methodology, validation, writing – review & editing, supervision.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability

All data supporting this article are provided in the supplementary information (SI) accompanying this manuscript (SI_SEF.docx; SI_Excel_SEF.xlsx). Supplementary information is available. See DOI: https://doi.org/10.1039/d5se01118c.

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