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Emissions-intensive and trade-exposed industries: technological innovation and climate policy solutions to achieve net-zero emissions by 2050†

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It is critically important to pursue the decarbonization of emissions-intensive and trade-exposed (EITE) industries in British Columbia (BC) and Canada and successfully integrate innovation-supporting policies with decarbonization policies designed to rapidly reduce industrial greenhouse gas (GHG) emissions. Focusing on EITE industries in BC, we have investigated the potential of decarbonization in five sectors: oil and gas, pulp and paper, aluminum smelting, cement clinker manufacturing, and mining. This paper examines available net-zero carbon technologies that these EITE industries could potentially adopt to achieve decarbonization targets. The key technologies identified are hydrogen, carbon capture and digitalization. Additionally, we identify continued innovation policy and support to promote the growth and prosperity of a low-carbon supply chain, BC's industrial competitiveness, and the scale-up of renewable companies and infrastructure. To aid public and private sectors in striving for sustainable pathways to decarbonization, we have developed a Technology Roadmap for BC to help policymakers and firms formulate a climate change mitigation strategy employing innovative technologies for large industrial emitters. Our analysis indicates renewable and low carbon intensity fuels such as hydrogen can play a vital role in reducing emissions across a wide range of BC's EITE sectors (*i.e.*, displacing diesel and eventually natural gas), thus having economic and environmental benefits for BC.

Sustainability spotlight

Achieving global greenhouse gas (GHG) emissions reductions to net-zero by 2050 requires the decarbonization of emissions-intensive and trade-exposed (EITE) industrial sectors. Using British Columbia, Canada as a case study, a Technology Roadmap was developed for five difficult to abate industrial sectors: oil and gas, pulp and paper, aluminum smelting, cement clinker manufacturing, and mining. The roadmap is designed to provide policymakers and firms a means to develop GHG reduction and technology innovation strategies to both mitigate EITE emissions and to develop BC's clean energy sector. This work focuses on the UN sustainable development goals of affordable and clean energy (SDG 7), industry, innovation, and infrastructure (SDG 9), climate action (SDG 13).

1. Introduction

Anthropogenically induced increases in the earth's temperature are possibly the most significant challenge facing society today, requiring cooperative efforts worldwide to keep potentially cataclysmic changes in climate from occurring.[1,2] Carbon dioxide (CO_2) emissions, as the primary cause of warming, need to be reduced dramatically or eliminated wherever possible if significant shifts in climate are to be avoided.[3–6]

1.1. Emissions-intensive and trade-exposed industries

Emissions-intensive and trade-exposed (EITE) industries use facilities that release large amounts of "hard-to-abate" emissions during manufacturing, which face significant provincial, national and international competition for their products. These industries are at the most risk of losing competitiveness in the short term if they are subjected to a price on GHG emissions that their competitors in other countries are not.[7] Emissions reduction policies[7] must take account of trade competitiveness imperatives if BC is to meet its international GHG emissions target while maintaining manufacturing sector competitiveness.[7,8] The Standing Senate Committee on Energy, Natural Resources and Environment has emphasized "Canada's GHG reduction targets have significant effects on five sectors of the Canadian economy: electricity, transportation, oil and gas, buildings and EITE industries that are mostly heavy industries that compete in international markets."[9]

Special consideration must be given to EITEs because, if faced with sudden, substantial changes and cost increases in their operations, demand for their products could transfer elsewhere in the global market without reducing worldwide emissions.[2,7,10] GHG reduction is a global collective action

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problem in that virtually all countries must participate to produce the desired outcome. Thus, efforts by one country to unilaterally reduce emissions in its EITE industries will cause competitive problems regarding the industries located in countries that lack stringent GHG-reducing policies. This competitive loss is sometimes referred to as "carbon leakage" to denote that any shifts in production could likely leak the emissions to elsewhere on the planet rather than reducing them.[2]

Canada's GHG emissions (Fig. 1), as reported in 2019, were 730 Mt, unchanged since 2005. With 19.7 tonnes of CO_2 per capita emitted, this makes Canada's emissions the third-highest per capita amongst the thirty-six Organisation for Economic Co-operation and Development (OECD) members.[11] Nevertheless, Canada has implemented climate policies, including a nationwide carbon price, which is reflected in the cost of fossil fuels used in all sectors of the economy.[12] Fig. 1 illustrates Canada's GHG emissions, broken out by economic sector, which is displayed on a map of Canada in Fig. 2.

1.2. EITE emissions in British Columbia

EITE industries in British Columbia (BC) are critical to the overall decarbonization plan to reduce CO_2 emissions. BC's Climate Action Secretariat[4] categorizes EITE industries based on the following qualitative criteria: firstly, greenhouse gas emitting industries that are covered by carbon pricing which cannot be mitigated cost-effectively; secondly, an industry's exposure to a competitive import/export market where costs are unable to be passed on to consumers without losing market share.[13]

EITE industries are hard to decarbonize because they produce and export commodity materials which are sensitive to price changes. The processes contributing to GHG for each EITE industrial sector in BC are described in Table 1. Decarbonization efforts are made further complex by industrial processes and infrastructure that are primarily compatible with conventional energy GHG emitting sources rather than those provided by innovative low carbon technologies. To transition industries away from high carbon-intensive energy, renewable and other low emitting energy sources will need to be compatible with existing industrial processes, allowing for their adoption at low cost. To survive, EITE industries will need to maintain continuous operation by having access to reliable sources of energy and consumer markets at a time where there will be rapid and significant transitions in both energy generation and consumer purchasing behavior.[6,15]

Solutions that capture CO_2 from facility emissions or directly from the atmosphere are also required for EITE decarbonization.[14] Technology options that include negative emissions such as direct air capture (DAC) and other carbon capture techniques will enable governments to implement more stringent decarbonization policies while potentially maintaining established homegrown carbon-intensive industries.[7,8,16] Carbon capture systems that both used and store CO_2 are often called carbon capture, utilization, and storage (CCU/S); here we use the term 'CCU/S'. However, while removing CO_2 is necessary, at least in the near-term future, the use of renewable and net-zero carbon sources of energy must be integrated if 2050 net-zero emission reduction goals are to be met. Industries have access to CCU/S and other technologies that would achieve a 100% fossil fuel global energy system with virtually zero GHG emissions, but the cost is currently too high for 100% adoption in EITE sectors.[17]

BC's total GHG emission inventories, measured in tonne of CO_2 equivalent (tCO_2e), is collected by government for the five main EITE industrial sectors. Aluminum, Cement, Pulp and Paper, Mining, and Oil & Gas, based on their NAICS Code, company name and facility name are shown in Table 2 and Fig. 3a. The transportation sector is not considered an EITE industry, however, oil and gas production and transportation emissions data are included. The bar plot in Fig. 3b demonstrates that BC's oil and gas sector has the largest carbon footprint compared with BC's remaining EITE sectors. The bar plot in Fig. 3c displays total BC oil and gas sector GHG emissions (tCO_2e) by production, transportation and refining.

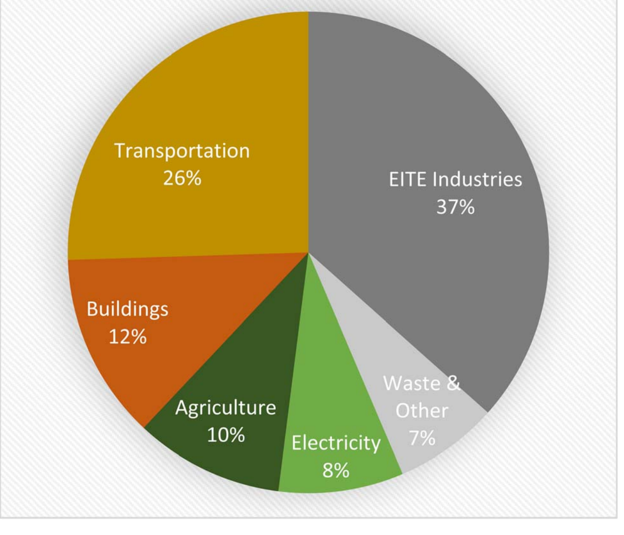

Fig. 1 Canada's GHG emissions, broken out by economic sector. Image: adapted from National Inventory Report 2021.[14]

1.3. Emerging low-carbon intensity technology

Carbon intensity or emission intensity is the emission rate of a given pollutant relative to the intensity of a specific activity, or an industrial production process, specifically the amount (gram) of CO_2 released per megajoule of energy produced, or the ratio of GHG emissions produced to gross domestic product (GDP).[18] Carbon intensity considers the GHG emissions associated with all the steps of producing, transporting, and consuming a fuel also known as the complete life cycle of that fuel.[18] Carbon intensity of energy sources is expressed in grams of carbon dioxide equivalent per megajoule of energy provided by that fuel.

Low carbon intensity technologies are rapidly improving, making it easier for EITE industries to reduce emissions and thus enable governments to implement more stringent emissions policies. Innovative technologies continue to emerge to

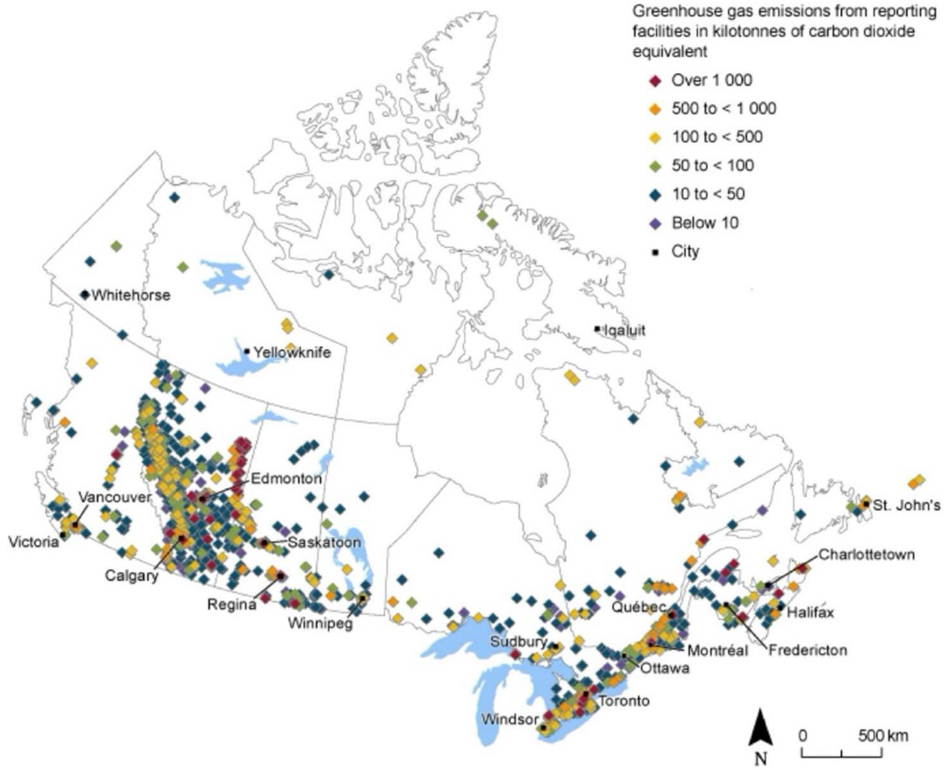

Fig. 2 2021 facility greenhouse gas (GHG) emissions. Image: courtesy of Environment and Climate Change Canada (ECCC).[19]

potentially accelerate decarbonization. Solar Photovoltaics (PV), wind turbines, clean hydrogen, and CCU/S are emerging low carbon intensity technologies relevant to EITEs.

Costs of PV modules and wind turbines have been reduced by nearly 90% and 60%, respectively.[20] The cost of constructing and operating wind and solar power plants, as being non-dispatchable electricity, can be compatible with resources that produce dispatchable electricity, with dispatchable electricity being up to 10 times more valuable.[21] Utility-scale battery storage technology is also improving and becoming less costly,

Table 1 The processes contributing to GHG for each EITE sector in BC[22]

EITE industries	
Aluminium sector	Primary aluminum production through smelting and refining and secondary aluminum production in which aluminum is recovered from aluminum-containing scrap.[23,24]
Mining sector	Overburden removal, drilling in rock, blasting, crushing of rock, loading of materials, transporting raw materials by conveyors, scraping, bulldozing, grading, open storage pile losses and wind erosion from exposed areas.[25,26]
Cement sector	The entire process of cement production in rotary kilns, as well as the preparation of concrete and ready-mix concrete, lime manufacture and concrete batching and products[27]
Pulp and paper sector	Chemical, mechanical, recycling, and semi-chemical mills, including the production of energy through the combustion of spent pulping liquor, biomass, and fossil-fuel combustion. Also includes fugitive emissions from wood refining, screening, and drying, and various steps in chemical recovery systems[28]
	Sawmills, panel board mills (including veneer, plywood, waferboard, particleboard and medium-density fiberboard mills), and other wood products manufacturing establishments (including furniture and cabinet makers, wood treating plants, wood pellet mills and Masonite manufacturers)[29]
Oil and gas/Refine petroleum products sector	Electric power generation from the combustion of fossil fuels by utilities (both publicly and privately owned) for commercial sale and/or private use[30]

Table 2 EITE sector GHG emissions in BC 2018 (data gathered and analyzed by the author from BC stats[31]). Total GHG emissions by tonne of CO_2 equivalent (tCO_2e) collected for EITE firms is based on their NAICS Code (a classification within the North American Industry Classification System), company name and facility name

Primary activity NAICS code & description	Company name	Facility name	Grand total emissions tCO_2e
211113-Conventional Oil and Gas Extraction	ARC Resources	ARC BC LFO	359 529
211113-Conventional Oil and Gas Extraction	Canadian Natural Resources Ltd	CNRL BC LFO	1 124 122
211113-Conventional Oil and Gas Extraction	EnCana Corporation	Encana BC LFO	987 348
211113-Conventional Oil and Gas Extraction	NorthRiver Midstream Inc.	BC Midstream (LFO)	417 803
211113-Conventional Oil and Gas Extraction	PETRONAS Energy Canada Ltd	Petronas Linear Facilities Operation	543 546
211113-Conventional Oil and Gas Extraction	Spectra Energy Transmission	SET PLFS (LFO)	2 692 139
211113-Conventional Oil and Gas Extraction	Tourmaline Oil Corp	Tourmaline LFO	427 722
211113-Conventional Oil and Gas Extraction	Canadian Natural Resources Ltd	BC Aggregated Facilities (<10 000 tCO_2e)	558 348
211113-Conventional Oil and Gas Extraction	Spectra Energy Transmission	Fort Nelson Gas Plant	503 025
212114-Bituminous Coal Mining	Teck Coal Limited	Elkview Operations	458 448
212114-Bituminous Coal Mining	Teck Coal Limited	Fording River Operations	573 128
212114-Bituminous Coal Mining	Teck Coal Limited	Greenhills Operations	408 459
322111-Mechanical Pulp Mills	Catalyst Paper Corporation	Powell River Division	671 467
322112-Chemical Pulp Mills	Canfor Pulp Ltd	Prince George Pulp & Paper Mill	2 118 021
322112-Chemical Pulp Mills	Cariboo Pulp and Paper Co	Cariboo Pulp and Paper Company	1 318 150
322112-Chemical Pulp Mills	Catalyst Paper Corporation	Crofton Division	1 674 233
322122-Newsprint Mills	Catalyst Paper Corporation	Port Alberni Division	427 714
322112-Chemical Pulp Mills	Canfor Pulp Ltd	Northwood Pulp Mill	1 487 002
322112-Chemical Pulp Mills	Domtar Inc.	Kamloops Mill (SFO)	1 327 266
322112-Chemical Pulp Mills	Howe Sound Pulp & Paper Corp	Howe Sound Pulp and Paper Mill	1 446 618
322112-Chemical Pulp Mills	Mackenzie Pulp Mill Corp.	Mackenzie Pulp Mill	697 670
322112-Chemical Pulp Mills	Mercer Celgar Ltd Partnership	Mercer Celgar Limited Partnership	1 330 736
322112-Chemical Pulp Mills	Nanaimo Forest Products Ltd	Harmac Pacific Operations	1 283 000
322112-Chemical Pulp Mills	Skookumchuck Pulp Inc.	Skookumchuck Operation	986 342
324110-Petroleum Refineries	Parkland Refining (B.C.) Ltd	Burnaby Refinery	427 960
327310-Cement Manufacturing	Lafarge Canada Inc.	Richmond Cement Plant	658 346
327310-Cement Manufacturing	Lehigh Hanson Materials Ltd	Delta Plant	873 630
331313-Aluminum Production	Rio Tinto Alcan Inc.	Rio Tinto Alcan Inc.	836 570
486210-Pipeline Transportation of Natural Gas	TransCanada PipeLines Ltd	TransCanada Pipeline, BC System	396 605
486210-Pipeline Transportation of Natural Gas	Spectra Energy Transmission	Transmission Mainline	1 080 113
Summation			28 095 058

as the energy cost for lithium-ion battery storage dropped 76% by 2019,[32] resulting in easier decarbonizing of electricity systems, particularly in the mining and aluminum sectors. Development of battery and storage technologies will complement non-dispatchable renewable energy investments by storing excess variable renewable generation, thus permitting renewable electricity sources to replace more reliable and consistent fossil fuel based generation without major new investments in conventional and dispatchable large hydro electricity.[33]

Hydrogen could be considered a promising clean, zero-carbon fuel[1,10] to replace carbon-intensity fuels such as oil & gas and coal. The challenge is that while hydrogen exists in nature, it is not capturable in that state. As such, hydrogen is not a primary energy source. Instead, it is an energy vector (a form of secondary energy), like electricity, heat, processed natural gas and refined petroleum products. Recently, the rate of development of facilities for hydrogen production has increased in North America compared with the past decade.[15] The potential for hydrogen to transform Canada's economy to a low-carbon future was discussed at the 13th Canadian Science Policy Conference (CSPC)[34] as well as at the Canadian Climate Institute (CCI), where experts from diverse disciplines gathered together to undertake rigorous research and conduct insightful analyses.[6] However, there is still a need for a range of innovative technologies to utilize hydrogen as a source of industrial decarbonization and the need for transformative policy support by BC's provincial government. Clean hydrogen can be made through several production methods, including biomass and water electrolysis. A recent update on progress in the Canada's emerging hydrogen marketplace,[35–37] showed that a lack of sufficient levels of research and development (R&D) funding and large-scale investments may cause a slowdown in an expansion of hydrogen production and use that could achieve emissions reduction targets.[38]

Recent studies and strategies have compared clean and renewable technologies, typically assuming high carbon capture rates,[16] but have not assessed the impact of fugitive emissions and carbon leakage, nor the capture rates on both total emissions and costs.

1.4. Assessing the potential for emerging decarbonized EITE industries through technology roadmapping

Several innovation-management tools can usefully inform policymakers and the industry about the potential for emerging

Fig. 3 (a) The bar plot displays total GHG emissions (tCO_2e) for each BC company and facility classified as EITE; (b) total GHG emissions (tCO_2e) collection by sector, Aluminum, Cement, Pulp & Paper, Mining, and Oil & Gas; (c) the bar plot displays total GHG emissions (tCO_2e) breakdown in BC's Oil & Gas sector. Notes: oil & gas and mining are not directly shown. Source: Authors' analysis based on data from the Government of British Columbia.[39]

decarbonized EITE industries. Two examples are technical-economic cost modelling of breakthrough laboratory inventions and technology roadmapping. Assessing development and commercialization priorities for a novel hydrogen production process was investigated by Maine *et al.*[40] through a technical-economic cost model that suggested distinct areas of competitive advantage for green hydrogen *vs.* blue hydrogen technologies. Steam Methane Reforming (SMR) has a price advantage in large scale production volume applications, but modular solutions can make sense currently in remote communities and smaller volume applications.[40] CCU/S technology may follow a similar trend due to the scaling-up effects.

Many studies (IRENA,[41] PEMBINA,[11] Foresight CAC[42]) have reached this conclusion. In a peer-reviewed engineering journal *Applied Energy*,[43,44] researchers compared the emissions and financial cost of producing hydrogen using fossil fuels or renewable energy: emissions from gas- or coal-based hydrogen systems are substantial even with CCU/S.[44] Fugitive emissions are rarely included in provincial and national H_2 strategies.[15,44,46] CCU/S is an expensive option for decarbonizing hydrogen production[57] while electrolysis with renewable energy could become cheaper than fossil fuels coupled with CCU/S.[48,49] In general, the technology path that results from our policy recommendations (on innovation or GHGs) should ensure net-zero GHG emissions.

In this paper, we develop and discuss a Technology Roadmap for EITE industries in BC, where homegrown innovation drives new advances and keeps BC's industries competitive while meeting climate targets within these industrial sectors. Technology strategy from roadmap to action for the next three decades is demonstrated below for BC's five main EITE industrial sectors: aluminum, pulp and paper, oil and gas, cement, and mining.[42] Furthermore, we report a pathway for a homegrown, innovative technology analysis to assess the state of relevant technologies and identify critical R&D opportunities to improve further cost competitiveness and lower GHG emissions.

Our study's primary goal is to evaluate different clean technologies and innovative technology options to ensure energy security for BC's EITE industries, thereby establishing the technology roadmap as a critical tool to achieve BC's decarbonization goal by 2050. Our research question is, "How can innovation policy complement decarbonization policies to achieve economic and climate goals in the EITE sectors in BC." We address this research question through a case study analysis of BC EITE industries and a technology roadmap of the innovative technologies which can achieve decarbonization.

2. Methodology

Our analysis for developing a technology roadmap aims to support cleantech leaders and policymakers to understand the timeframe and interrelatedness of development and decision-making for BC EITE industries and BC innovative technologies. An urgent shift from contemporary industrial technology and policy is required to achieve decarbonization by 2050. Our roadmap could help BC's EITE industrial leadership to be more strategic when making investment decisions or managing innovative technology projects and be better prepared for discussions with other EITE industries within the value chain when they request new projects or initiatives. Thus, we offer recommendations for how the BC government can set the conditions to accelerate the adoption of innovative emission reducing technologies within BC's five EITE industrial sectors. We reviewed, curated and analyzed a wide range of works in the literature, including reports and assessments on innovative technologies within corporate and academic R&D laboratories at various development stages from emerging, to scale-up, to full commercialization, enabling us to propose a comprehensive industrial policy framework for EITE industry decarbonization.[50–52]

Our methodology used to develop a decarbonization Technology Roadmap for BC's EITE sectors consisting of four phases of research and analysis:

(1) Evidence gathering and processing based on literature.

(2) Analysis of net-zero pathways incorporating BC's preferences and constraints within each EITE sector. Benchmarking overall levels of CO_2 emissions reductions that correspond with net-zero goals.

(3) Testing and developing a final pathway that requires vast amounts of investment, innovation and technology deployment, infrastructure modifications, policy implementation, and cooperation across the EITE industries within BC and nationwide. Validating and refining the roadmap through interviews and Pacific Institute for Climate Solutions (PICS) hosted workshops.

(4) Implementing short-term and long-term decarbonization policies and actions necessary to achieve a net-zero by 2050 emissions target.

The timeline of our roadmap was set out to achieve a commitment of having five low-carbon EITE sectors by 2030 and the first net-zero EITE sector by 2040. Our technology roadmap development was based on a comparison of the key points arising from each emissions-reducing innovative technology within its specific value chain segments. Due to the various processing routes of EITE industrial produced materials to the end consumer,[53] and their comparatively low emissions, we have not included in our analysis the downstream processing segment of EITE industries, *i.e.* aluminum, cement and mining into different end-use products. We used an illustrative combined set of four action pathway categories, knowledge and capacity, production or supply, market development demand, and infrastructure material/energy modification (Fig. 9) to facilitate EITE industrial decarbonization. The four categories of actions can be combined for each EITE sectors to show how the most practical or timely elements from each of the innovative technologies can be coordinated to achieve industrial decarbonization. This roadmap could provide government decision makers with insights into potential decarbonization pathways for BC's EITE sectors. The phases used in our analysis to create a novel roadmap are as follows.

2.1. Technology roadmap development: evidence-gathering and processing

We reviewed roadmaps for several innovative technologies and associated cost curves developed in the literature and by policy, government, and consulting groups. Notably, we captured how future technology costs are projected to decrease through to 2030 and 2050. The roadmap is developed through a structured series of steps involving technological and market experts and policymakers. We used secondary sources to gather 2018 emissions data on BC's EITE industries using the federally funded Canadian Energy and Emissions Data Centre (CEEDC).[53] We reviewed and incorporated major Canadian roadmaps[33] on the Clean Energy Transition and selected international roadmaps such as from the International Energy Agency (IEA),[54] IPCC,[55] IRENA[41] and FCH.[56] We adopted the resources provided by analysts from most recent reports, such as Foresight CAC, the U.S. DOE, Frost and Sullivan, DNV, COP26, IEEE, PEMBINA, CORE Clean Cluster, NRCan, CleanTech BC, Clean Energy Canada, Canadian Institute for Climate Choice (CICC), and more. The adapted information was newly created or changed to be compatible with BC and Canadian resources.

We curated those documents for clean energy solutions in the EITE sectors that are most relevant to our policy integration work. Given our expertise in hydrogen production and CCU/S, we were able to take publicly available information on these areas and collate it to inform BC EITE sectors' decarbonization policy. Our team collaborated with Simon Fraser University's Energy and Materials research group to assess and incorporate technical-economic cost data which has been developed by energy modelling experts,[7,57] including the federal government's Canadian Centre for Energy Information, Canada Energy Regulator, the U.S. Department of Energy (DOE) Energy Information Administration and the U.S. DOE National Renewable Energy Laboratory.[58]

Initial technology roadmap inputs were developed by conducting a global literature review on existing research, roadmaps, technical-economic cost modelling methodologies and results.[33,54] Our roadmap contributes to the literature and policy discourse by integrating global analyses, applying them to BC's EITE sectors and demonstrating there are pathways to reach net-zero by 2050. Our study considers the potential to achieve emissions reduction targets, technical feasibility, cost--effectiveness, and economic impact in decarbonizing BC EITEs sectors.

Our in-depth literature review looking into currently developed roadmaps and hydrogen strategies reports for Canada and BC provided us with a clear picture of BC's EITE industry infrastructure capabilities and how they align with their decarbonization goals. We adapted this information to be compatible with BC and Canadian context. Secondary data was collecting to assist with forming a complete profile of BC EITE industries.[53] Secondary sources include Genesis Advanced Technology, governments of BC and Canada, Sustainable Development Technology Canada (SDTC), and through Cleantech companies' documents, published interviews of industrial leaders, and publicly available information on the company websites. Following Maine *et al.*, these data are supplemented by in-depth searches for research papers, magazine articles and case studies on emerging innovative technologies, their competitors, and technology suppliers.[57] A case study approach, is particularly well-suited to develop an understanding of emerging innovative technologies for industries, specifically for addressing "how" and "why" questions.[60,61]

2.2. Technology roadmap development: BC's preferences and constraints pathway

Based on our sectoral analysis of EITE industries in BC, we investigated and developed steps of potential innovative technologies for decarbonization (*e.g.*, green hydrogen, CCU/S and zero-emission/low carbon-intensity fuel production) and a roadmap for their deployment. The analysis considers the primary value chain steps: supply, distribution, storage-conversion, and end-use applications. Initial technological data were obtained from publicly available sources and a database was developed on new ventures and incumbent corporations originating from academic start-ups taking the initiative to develop zero-emission technologies.[62,63] The next step was adopting recent (2020–2023) technology roadmap frameworks and combining them with BC-specific technological data[51] to develop roadmaps tailored to the BC context.

We investigated the emergence of the green and clean hydrogen sector, which has promising attributes in BC, to develop guidelines for clean hydrogen technology start-ups in emerging innovative technology for the EITE industries. Collecting publicly available secondary data from various sources (including government, regulatory agencies, and company websites), along with online meetings in hydrogen strategy from the founders/CEOs/VPs, allowed us to engage in data analysis to mitigate concerns about the reliability of the study.[64] These meetings were conducted during interviews with five industry professionals with engineering design and business development experience. One of the meetings was with a representative from the CCU/S design industry in BC, and another was with an active party in membrane development for green hydrogen production *via* electrolysis.

2.3. Technology roadmap development: developing and validating pathways

We identified low-cost technology approaches by removing unnecessary and inefficient applications and technology. The critical pathways identified to decarbonizing EITE industries are: (1) lowering the demand of industrial products by increasing their reuse and recycling; (2) adapting and deploying the best available technologies to reduce energy use per production volume; (3) electrification by replacing fossil fuel with renewable electricity; (4) replacing fossil fuel with sustainably produced biomass and/or low carbon-intensity hydrogen; (5) adapting processes with CCU/S; and (6) developing innovative processes (*e.g.*, electrochemical production processes) to reduce emissions. In our roadmap development, we allowed for complementary solutions to rely on technological, organizational, and behavioural changes that must be pursued in parallel and throughout whole of the industrial value chains of each EITE sector. Engagement between government decision-makers and industry solution-seekers was a continued factor during our analysis.[65]

Our roadmap provides the relevant timelines and milestones of low-emission innovative technologies that meet BC EITE industries' production requirements. However, to avoid significant technology failures as much as possible, we considered any weaknesses within the industries' existing infrastructure that are currently known. Our roadmap was adapted to the global innovations trends outlined by the IEA[36,54] and local consideration through the input of secondary source analyses on clean energy in BC from 25 active companies,[53,66,67] of which

12 are the leading companies listed in Global Cleantech 100 (ref. 9) in CCU/S and hydrogen technologies. To achieve decarbonized EITE industries in BC, a joint effort by investors, industries, and policymakers to foster an acceleration of innovative activities along the value chain are required, including industry alliances and companies heavily investing in R&D to developing new low carbon-emitting products. Both industry and regulators must coordinate to push for the enforcement of long-term objectives for decarbonization in general and hydrogen in particular.

We validated our roadmapping methodology by soliciting feedback on our initial analysis through interviews with relevant policy experts and Cleantech industry professionals, including Aaron Hoskin of NRCan,[15] and David Sanguinetti of Foresight CAC, and PICS.[49] We maintained ongoing collaborations with PICS, Foresight CAC, and BC-based universities throughout our analysis and continually engaged with a network of decision-makers in government and industry as part of designing, implementing, and presenting the results of our research.[68]

2.4. Technology roadmap development: creating actions and policies to achieve net-zero by 2050

Our technology roadmap incorporates a plan for the short-term (to 2030) and long-term (to 2050), considering the risk of losing competitive advantage for BC's five EITE industrial sectors. Our primary work represents measures to scale lab-based technologies to full commercialization.[69] Zero emission industries require innovative clean and renewable energy technologies to facilitate fuel-switching across the whole material value chain, the implementation of carbon capture in difficult to abate processes and other measures reduce end-use demand through recycling and other novel end-of-life process.[52,70] It is also vital to complement R&D technology by reshaping markets and strengthening governance capacities in this emerging technologies and policy domain.

Studying various BC-based innovative technologies[71] in varying stages of technology readiness levels (TRL) and best available technology (BAT) within the value chain for each specific tech mechanism greatly contributed to our analysis. The results of this study incorporated R&D and production capacity, market development potential, and supporting infrastructure modification for the five chosen BC EITE industry sectors. We conducted an examination of available cost-effective zero-carbon technologies and industrial processes to develop our decarbonization roadmaps and a ventures database.[53] Various pathways among BC's industries were developed to consider the impact of potentially successful and sustainable joint efforts between EITE industrial sectors to decarbonize.[42]

Our research intends to advance prevailing Energy-Economy-Emissions Models and develop their capacity to assess decarbonization and innovation technology mixes for EITE industries and analyze different combinations of innovation and climate policies under diverse circumstances to reach a net-zero emissions target by 2050.[1] While it was beyond the scope of this study to conduct sensitivity analyses on the many different parameters such as the emissions intensity and trade intensity of the five industries studied, important uncertainties were identified and explored in our technology roadmap methodology.

3. Results

To create a technology roadmap for decarbonizing BC EITE sectors, we investigated and compared various recommended climate actions, policies, and technology solutions to address GHG emissions. We collated this information from previous and recent reports which provided the foundation of our recommended actions that can be applied to the top five of BC's EITE industrial sectors (Table 2). In this section, BC specific findings about the decarbonization of BC EITE sectors are presented, followed by innovative technologies which could address BC decarbonization needs. Finally, a comprehensive technology roadmap for BC EITE industries is presented.

3.1. Decarbonization considerations for BC's five EITE sectors

Relevant manufacturing operations and clean energy transition initiatives were assessed for BC's five EITE sectors, including technology and process type, name, description and solutions, state of development, GHG impact, energy impact, and cost (Tables S1 to S5 in ESI Material†). Findings that are most relevant to the technology roadmap for each sector are presented here.

3.1.1. Cement sector and coal utilization. BC's Lafarge Portland cement clinker contains four principal chemical compounds, which are generally referred to as clinker minerals (Fig. 4). Calcination of limestone and burning of fossil fuel (mainly coal and petroleum coke) to heat the material at high temperatures makes the cement manufacturing process very carbon-intensive (around 650 kg of CO_2 per tonne).[18] Such process-intrinsic emissions account for the majority of associated emissions.[66] Cement production embodies 5% of worldwide CO_2 emissions.[67] Sequestration of CO_2 in concrete (*e.g.*, technology by the Canadian-based CarbonCure) permanently locks captured CO_2 in concrete and upon injection into concrete during mixing, the CO_2 is converted into a mineral integrated into the concrete. Even if building structures composed of carbon cured concrete is demolished, mineralized CO_2 will never leak or return to the atmosphere.[72] The development of new process chemistries that remove associated CO_2 process emissions is critically important for decarbonizing industry since they account for a significant percentage of global emissions.

A summary of all the components necessary to decarbonize cement production processes:

(1) Carbon curing will provide partial reductions by increasing both CO_2 efficiency and output efficiency.

(2) "Clinker Substitution" partially reduces clinker use per output of cement or replace with 'alternative clinker'.

(3) Decarbonizing clinker production could be done by:

(3a) CCU/S for process emissions (when lime is heated), and

Cement -Lafarge Canada Inc. (Richmond)
t CO_2 e = 658,346 in 2018 report Table2

Cement -Lehigh Hanson Materials Ltd. (Delta)
t CO_2 e = 873,630 in 2018 report Table 2

Fig. 4 Lafarge Canada Inc. (Richmond) and Cement – Lehigh Hanson Materials Ltd are the two sectors located across the Fraser River in BC. Image: courtesy of Google Map.

(3b) decarbonizing kiln heat source with CCU/S or fuel switching to electricity, biofuel, or hydrogen.[44]

The Heidelberg Cement Group (Fig. 4) has taken the initiative to decarbonize their processes in three approaches: (1) development of alternative clinker; (2) CCU/S technologies; and (3) developing a composite cement containing less clinker.

In the "Acceleration and Scale-up" stage of technology development, capturing unavoidable process emissions, reusing the CO_2 in cement industries, and boosting bio-based concrete[73] can be achieved starting with 10 000 tonnes per year of production in 2030.

Zero-carbon cement includes all direct CO_2 emissions associated with its production and lifetime servicing, as well as all sequestration options, such as engineered re-carbonation, the use of supplementary cementitious materials (SCM) or carbon-free energy sources, electrification, and CCU/S technologies, followed by growth and diversification of the sector in the 2025–2030 timeframe. These technologies are considered in our four action lines (Fig. 8), and in our roadmapping (Fig. 9). As the technology matures or reaches appropriate TRL stages for commercialization, carbon storage use can be focused on applications that provide the best value proposition relative to other zero-emission technologies.

3.1.2. Pulp and paper sector. The pulp and paper sector is one of the five most energy-intensive BC industries that consumes 60% of all final energy. High-grade heat is this sector's most significant GHG contribution, with about 40% of energy demand, and electricity has the lowest share.[56] Electrification is one candidate as a cost-efficient alternative for decarbonizing low- and medium-grade heat pieces of the pulp and paper sector, which could be feasible in BC since approximately 98% of all electricity in the province comes from hydropower. However, the most significant contributor to GHG within all of BC's EITE industrial sectors was identified to be Canfor Inc. in northeast BC.

Mechanical pulp mills in BC have always been driven by electricity, ~100% machine-controlled to separate wood fibres to make pulp.[74] While, in chemical pulping, wood fibres are separated through chemical reactions generated with heat, where most decarbonization has occurred by taking the biomass waste from the chemical reactions (known as Black Liquor) to use as an energy source to drive the heating process. Hence, it is a promising approach to decarbonizing heat in the pulp and paper industry, suggesting that black liquor is an option to explore. All black liquor from thermo-chemical pulping, fuels synthesized from biomass *via* thermochemical conversion processes,[66] have been recovered and burned to generate heat since at least the 1960s.[75] This on-site recycling process is likely the most accessible and cost-effective way for which pulping mills are rapidly decarbonizing. Electrification could have a high potential for any machinery.[76,77] Another approach is investing in producing renewable hydrogen as a heat source. Therefore, the above discussion has been considered for the production or supply action line in our roadmapping (Fig. 9).

BC's pulp and paper sector has taken initiatives toward reducing their emissions by adopting technology or process type innovations (shown in S2 in the ESI Material†). Developing renewable energies, such as biomass, geothermal, and heating pumps, and circular reuse of wasted high-grade heat, can support industries to use new low-GHG equipment and, importantly, the use of biomass as a feedstock for high-temperature production processes in both the cement[78] and the pulp and paper industries.[79] The projected deployment of hydrogen would create an estimated $100 billion industry for the fuel and associated equipment for BC sectors by 2030, reaching over $200 billion by 2050.[45] Process emissions are also in the pulp and paper sectors. There is no other way to reduce process emissions except by capturing them.

3.1.3. Aluminum sector. BC produces the highest quality and lowest-carbon footprint aluminum globally. Canada imports bauxite minerals as a feedstock for aluminum production through international supply chains from major trading nations by importing bauxite from the equatorial regions of Brazil, China, Guinea, and Australia.[80,81] In Canada, aluminum production is primarily located in Quebec, known as Atlantic Operations consisting of bauxite to alumina refining operations, the main ingredient in aluminum, and alumina to aluminum smelting. Atlantic Operations release CO_2 emissions partly due to the fact alumina refining requires significant amounts of emissions intensive energy. Hall-Héroult electrolytic process used for producing aluminum from alumina in Quebec is also associated with emissions.[66] Clean and renewable innovative technologies could potentially play a role in helping to reduce aluminum production emissions, but many have yet to reach the commercialization stage. R&D laboratories are helping to further develop a breakthrough in aluminum smelting innovative technology with no direct GHG emissions, given that both electrification and adoption of hydrogen technologies for heating could help reduce emissions in the aluminum industry.[23]

In BC, Rio Tinto's aluminum facilities have taken the initiative towards reducing their emission by adopting novel technologies and processes. The aluminum metal provided from Rio Tinto's Kitimat Aluminum Smelter in BC (Fig. 5a) is an example of a nearly decarbonized facility, as the metal electrolysis is powered by BC Hydro's clean and near carbon-free electricity.[82] Other decarbonization initiatives of Rio Tinto are shown in S3 in the ESI Materials.† While aluminum refining contributes to Rio Tinto's global emissions (Fig. 5b), BC's Kitimat Aluminum production facility is in a reasonably good position to achieve 100% decarbonization.

3.1.4. Mining sectors. The global clean energy transition will require large amounts of metals and minerals, which could be exported from Canada.[68] Canada could set a leading environmental standard for all Canadian mining companies to meet stringent decarbonization targets and export sustainably developed metals and minerals.[83] Canada also needs a transparent process for the mining sector to demonstrate that they meet those standards. Innovative technologies connected to BC EITE industries, with the growing demand for clean metals to build a clean energy economy, could potentially be more accessible to Canadian mining companies and stakeholders. However, the mining companies may step up and ensure they meet environmental and social justice practices of the highest standards.[84] Mining sectors in BC could meet the demand for renewable technologies by designing manufacturing technologies with low-cost processes driving productivity and market opportunities that could arise from scaling up manufacturing for existing stakeholders within the stream.[68]

BC has a competitive advantage in its innovative technologies, services such as digitization, considered in the road-mapping Knowledge and Capacity action line, Fig. 9, and policy expertise. While BC has a solid foundation in these areas, more can still be accomplished.[85] Considering our findings in the result section, increased operational efficiency, electrification,

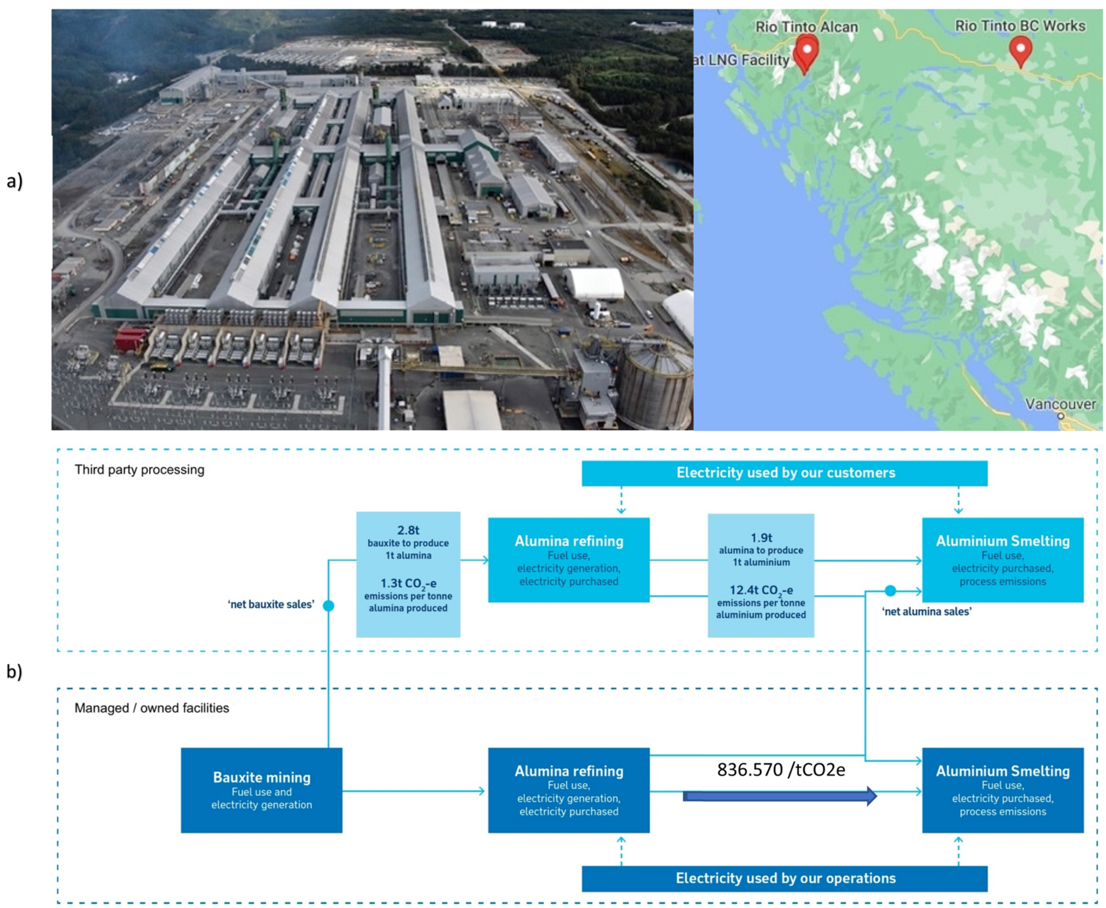

Fig. 5 (a) Rio Tinto Aluminum industry in the Northern part of BC. Image, Google Maps and RioTinto website. (b) The process contributing to Rio Tinto's global GHG emissions is demonstrated in the schematic. All rights reserved.[24]

and the utilization of renewable energy sources can create a carbon-free mining sector. The use of lithium batteries could aid mining decarbonization since BC and Canada already employ battery-electric technology for underground mining.[86]

The transition to a low-carbon economy creates increased demand for emerging commodities with new chemical properties that may enable innovative technologies. Fig. 6 shows BC mines, smelters, refineries producing copper, lead, zinc, and by-products, and advanced exploration projects[87] targeting copper and zinc.[68] While BC currently produces and processes most metals used in making solar cells, additional investments could sustain or expand the production of metals and minerals that convert solar energy to electricity.

3.1.5. Oil and gas sectors. BC currently produces one-third of Canada's natural gas and is well-positioned to ship significant volumes of Canadian oil and natural gas to meet growing energy demand in emerging Asian economies. BC has 1.8 trillion cubic feet (Tcf) per year, precisely 32% of Canada's natural gas production, and 16 000 barrels per day—about 2% of Canada's total daily conventional oil production. BC is a net exporter of energy and exports most natural gas to the U.S. and the rest of Canada. BC also exports electricity and imports refined fuel products. BC's oil and gas refinery, located in Burnaby since 1935, acquired by Parkland in 2017, this is one of Canada's only remaining West Coast refineries.[30]

With the addition of greenfield liquefied natural gas (LNG) facilities (such as LNG 1 and 2), BC's CO_2 emissions will rise significantly. If these liquefaction facilities combust unabated natural gas (*i.e.*, without CCU/S) when liquifying the gas for export, they would prevent BC from achieving its 2050 climate goals. If, however, they use electricity from zero-emission sources, they would have no impact on provincial GHG emissions and might contribute to some immediate reductions in global emissions by substituting for coal. Nevertheless, an opportunity does exist for the BC government to partner with this EITE industry to drive commercial hydrogen projects as part of the sector's net-zero agenda. As per our analysis, we estimated linear projections of the future cost of producing hydrogen from natural gas *vs.* from electrolysis from wind-based sources. There are many dynamics at play, for example, the price of natural gas could plummet as demand switches away from it, meaning that hydrogen from natural gas with CCU/S could potentially become cheaper. Also, if wind and solar are used to produce "green hydrogen" there are load factor issues for facilities that make it more expensive in many (but not all) situations – load factor being affected by the variability of both primary energy inputs. We evaluate this circumstance within the four lines of action in Section 3.4, and it is contemplated in our roadmapping in Fig. 9. Similarly, the chemical industry can move to adopt hydrogen as a feedstock with government support, as stated in the Hydrogen Strategy for Canada report in 2020.[15]

In the CleanBC roadmap report, BC is the first jurisdiction in Canada to set a specific sectoral target for reducing emissions from the oil and gas industry. The oil and gas sector contributes to 50% of industrial emissions in BC and 20% of the province's overall emissions.[30] Still, the only petroleum refinery in BC, the Parkland Refinery Ltd, is one of the minor CO_2 contributors compared with other EITE sectors such as pulp and paper and cement.

With high carbon capture rates in the oil and gas sector, it is estimated that the cost of producing blue hydrogen is \$2.87 (US\$2.09) a kilogram per tonne of CO_2, while the cost of building green hydrogen is \$4.99 (US\$3.64) per kg with projections that it may come down to \$2.55 (US\$1.86) per kg.[88]

3.2. Innovative technologies to prioritize for the decarbonization of BC EITE industrial sectors

To reach our 2050 emissions goals, near-term action needs to be taken to support developing and deploying innovative technologies to address the decarbonization of BC's EITE industries. To prioritize the technologies providing solutions to the decarbonization of BC's EITE industry sectors, we considered their anticipated commercialization timeline, their certainty of

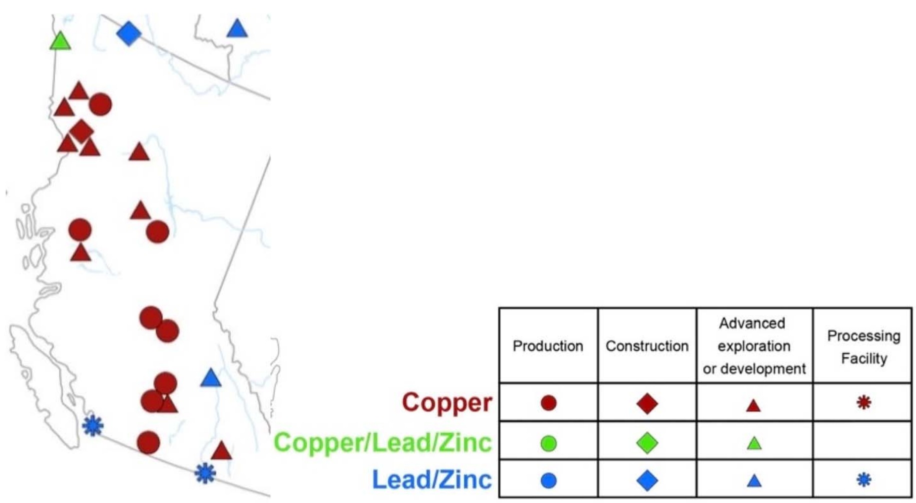

Fig. 6 Mines, processing facilities, and advanced exploration projects associated with inputs for solar cells. Image source: adapted from Government of Canada (NRCan).[87]

commercialization, their impact on carbon emissions, and their domestic capabilities. Technologies assessed in our roadmap include digital technologies, hydrogen, carbon capture, and electrification.

Digitalization is defined as using digital technologies, such as artificial intelligence (AI), big data technology, cloud technology, and robotics, to initially execute, control, and improve every tangible and intangible activity that together comprise the value chain,[89] leading to the creation of intelligent products and services, and other business model transformations.[90] Extensive research in the literature has shown that digitalization could contribute to reducing emissions in hard-to-abate EITE industrial sectors by transforming the entire value chain of the EITE industries.[91,92] Cost reductions within the value chain of EITE industries could occur when technological innovations in one industry accelerate a series of process and product innovations in other sectors. Digital and AI technologies support and carry a powerful potential in this respect.[93] Substantial GHG emissions reductions in hard-to-abate EITE industrial sectors can be achieved by embracing digital technologies.

Carbon capture and renewable hydrogen projects are still in the stage of Lab to Market, early commercialization and demonstration stages. Collaboration and partnerships between R&D academia and private institutions and companies must also be increased for hydrogen commercialization and scale-up, which could potentially reduce the costs associated with its value chain. Some transformative hydrogen and CCU/S technologies are still in the research lab or not yet invented. According to the International Energy Agency (IEA), this may account for nearly 50% of the technologies needed to meet our net zero global targets. For these nascent technologies, innovation and entrepreneurship training of STEM researchers can be a crucial component of accelerating solutions to market.[54] Early-stage innovation supports are also needed to de-risk, shape and scale clean energy innovation.[53,66]

Electrification will play a major role in BC's EITE sector decarbonization in aluminum, mining, pulp and paper, and cement. There will be the continued need for metal and minerals to supply a future low-carbon and clean energy transition, and thus the mining and other metal and mineral production sectors also need to push towards net-zero carbon emissions by 2050. In this results section, we show that BC's near clean electricity grid, which is far ahead of most countries, offers BC the opportunity to shift industrial processes to nearly 100% clean electricity, using that energy to power manufacturing sectors and other industries like mining, minerals and forestry to produce low-carbon products. Therefore, the electrification has been considered in the four action lines within our roadmaping (Fig. 8 and 9).

When integrating any innovative technologies within existing EITE industrial sectors, it is important to consider that these energy intensive industries are highly dependent on incumbent infrastructure such as power grids, gas pipelines, and railways to supply energy and current feedstocks. A shift in any production processes is often constrained by the current infrastructure and requires new investment to transition.[94] Individual companies and policymakers need to consider the cost implication of modifying the pre-existing infrastructure compared with newly developed infrastructure needed to support innovative technologies.

3.3. The competitive landscape in patent activity: green hydrogen production has promising attributes

Assessing the implementation of emerging hydrogen innovation technologies could potentially help in adapting innovative policy and action by the BC government to create more competitive and sustainable EITE industries in BC, while protecting high-paying jobs primarily located in rural communities.[95–98] The competitive landscape in intellectual property for hydrogen production derives from various companies within the value chain of energy, transportation, material, and industries. As shown in Fig. 7, most of the patent applications in hydrogen production *via* biomass conversion come from multinational material and chemical corporations such as Shell, Du Pont, Ionomr Innovations Inc.,[48] Ballard Power Sys., LOOP, ZEN Energy, AVL, Cummins, AltaGas, DSM, Quadrogen, and Anellotech.[99] Electrolysis, the critical technology in green hydrogen production, appears to be dominant compared to the other productions.

Major Canadian oil and gas companies,[100] such as Shell, Suncor Energy Inc. and Cenovus Energy Inc., down to small junior players based in Alberta, are highly interested in hydrogen production. These companies combined hold over 300 patents in hydrogen production.[99]

Electrolysis can achieve very low emissions if powered by renewable or nuclear energy. Solar power likely can achieve 1.0 kg CO_2eq per kg H_2 and wind 0.5 kg CO_2eq per kg H_2 in 2030, the difference resulting from the higher embedded Capex emissions for solar panels based on the projected 2030 scenario in IRENA's Global Renewables Outlook 2020 (ref. 41 and 99): 20% wind, 15% PV, 6% biomass, 15% hydro, 1% geothermal, 11% nuclear, 16% natural gas, and 16% coal. Electrolysis with run-of-river hydropower can achieve even lower emissions of 0.3 kg CO_2eq per kg H_2. Nuclear power achieves 0.6 kg CO_2eq per kg H_2, but it is also important to note that it leads to 0.115 g of radioactive waste per kg of hydrogen, based on spent nuclear fuel of 0.0021 to 0.0027 g kW^{-1} h^{-1} of electricity.

Capex-related emissions based on the global average grid mix of 66% renewable power in 2030 for asset manufacturing are very low across hydrogen production pathways. For fossil, nuclear, and most renewable power sources, Capex-related emissions are in the single-digit g CO_2e per kW per h range and a low double-digit number in the case of PVs.[101]

3.4. Technology roadmapping: the solutions for industrial decarbonization

Our innovative technological roadmap developed to address the decarbonization of BC's EITE sectors considers four interconnected lines of action. To reach BC's 2050 climate targets, four related sets of initiatives are recommended.

(1) Demonstration projects for Carbon Capture and fully Renewable Hydrogen to target production, storage, and utilization goals by 2030.

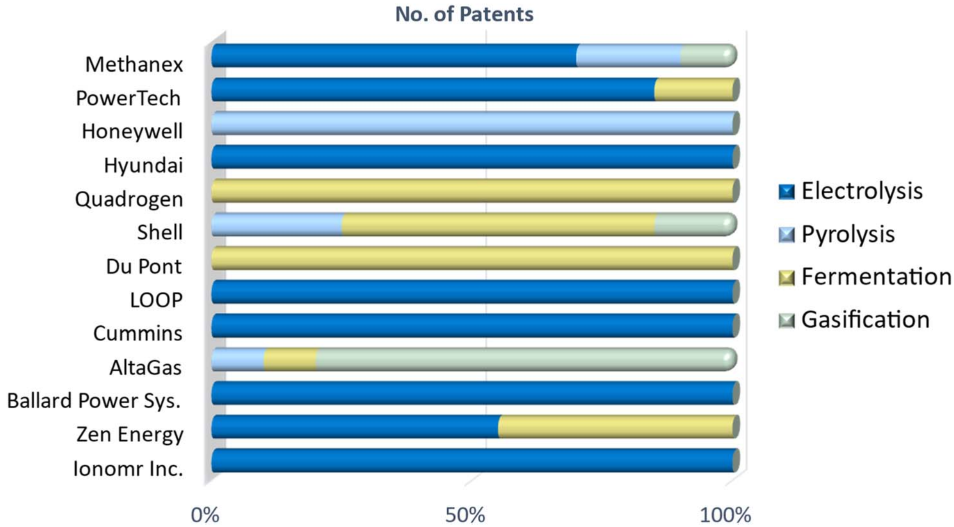

Fig. 7 Hydrogen production: Key Canadian Patent Assignee/Applicant, source: Authors' analysis based on data from Canadian Patents Database.[99]

(2) Increase investments in R&D activities related to innovative technologies and policies to incentivize support across new value streams to meet 2050 targets.

(3) Incorporate EITE industry infrastructure with on-site net-zero emission technology to handle production & delivery, leading to a rapid momentum for innovative technologies across EITEs.

(4) Develop a new revenue model for industries with an economic value proposition in lowering capital cost per unit of energy to accelerate the implementation of clean energy innovation.

The schematic in Fig. 8 emphasizes that all four action lines indicated on the Technological Roadmap (Fig. 9) must now be launched to achieve net-zero emission targets by 2050. BC's Hydrogen Strategy compares different hydrogen production methods based on the carbon intensity of each process.[102] It also proposes regulating industry to have a maximum allowable carbon intensity that decreases over time. Assuming that the rate of decrease is in line with BC's emission reduction goals, then the question of how to produce the hydrogen becomes one of economics. To explore the hydrogen technology landscape in detail, it is necessary to evaluate different forms of hydrogen production, including their key technical components, materials, processes, innovations, and market development opportunities in the value chain for each EITE industry sector. Frost & Sullivan[57] investigated the state of play of the electrolyzer market, discussing, among other topics, the role of technology service providers and recommended policies to stimulate innovation and R&D.[103] Therefore, the above-stated actions have been considered in our technology roadmap analysis.

The "Roadmap Foundation-to-Action," shown in Fig. 9, focuses on matching specific innovative technologies which EITE industries with an explanation of how these alternatives could be integrated. For example, clean hydrogen can be utilized to decarbonize several EITE sectors in BC, while also holding the potential to be a globally emergent and competitive clean energy transition industry. From this prioritization, we create a set of actions which are summarized and discussed in the upcoming sections.

Recognized as heavy industries in BC, oil and gas, cement clinker, pulp and paper mills, aluminum smelters, and the mining sector are the five largest CO_2 emitters among BC resource-based and manufacturing industries (Table 2). However, they rank differently along the two dimensions generally accepted for assessing whether a sector is at risk of carbon leakage, *i.e.* carbon intensity and openness to national and international trade. Asymmetrical climate policies cause carbon leakage, that is, policies that impose carbon prices in one jurisdiction,[2] in contrast to other jurisdictions that have no or less stringent climate policies and prices.[104] The cement and pulp and paper sectors are very carbon-intensive but only moderately open to international trade, while aluminum and mining feature lower carbon intensity but higher trade openness. The pulp and paper sector accounts for over 2 000 000 tCO_2e emissions and approximately 5% of total industrial energy consumption, contributing 2% of direct CO_2 emissions from industries.[105] Contributions of the Ore and Mineral and Manufacturing EITE sectors in BC towards GHG emissions can be found in Table 2.

The processes in each case that contribute to GHG emissions can be found in Table 1. There are several key components to consider in developing a clear pathway to achieve a low carbon-intensity economy, such as scaling up innovative technologies, rapidly bringing down their cost, investment priorities for specific technologies, the role of policies in creating demand for hydrogen, determining effective ways to produce hydrogen, determination and certification of quality and safety standards, and the development of hydrogen storage and transport, including blending hydrogen in natural gas pipelines.[106,107]

Decisions on green *vs.* blue hydrogen also have implications. For example, moving forward with green hydrogen requires the assumption that blue hydrogen infrastructure will eventually

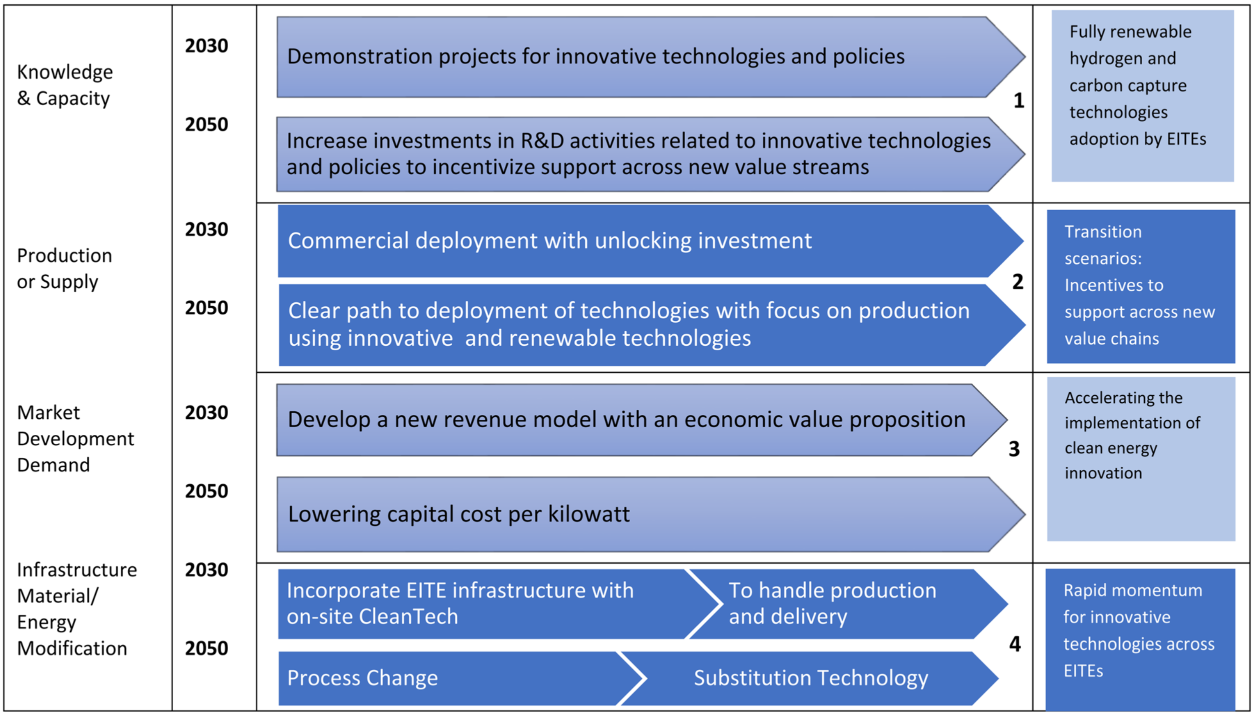

Fig. 8 All four interconnected sets of initiative lines for 2030 and 2050, indicated on the Technological Roadmap, that must be launched to achieve the net-zero emission targets by 2050. Source: Authors' analysis.

become stranded assets and that the cost of infrastructure modifications for the adoption of zero-carbon energy sources by EITE industries while taking into account the cost of green hydrogen production is predicted to decrease faster than blue hydrogen.[44] This topic is discussed further in Section 4.3 and 4.4.

The schematic in Fig. 9 shows a technology roadmap and action pathways for EITE industrial decarbonization. The recommendations proposed in this roadmap could potentially help BC to identify a significant potential innovative technology to address a range of energy needs, along with opportunities for BC EITE industries to meet the demand for these innovative technologies and navigate its energy system transformation and pathway to decarbonize by 2050. With the need to address climate change and reach net-zero emissions, CO_2 must be cut drastically from all areas of life, including EITE industrial sectors for which the emissions are challenging to abate. With increasing recognition that hydrogen, as one of the innovative technologies, could potentially play a key role in transforming these sectors, comes the challenge of deploying new technologies at scale to support the shift to a hydrogen economy.[59]

Fig. 10 shows the five EITE sectors' GHG emissions over 2020–2050 when implementing the innovative technologies, and policies recommended in our roadmap. From the data gathered and analyzed in this study, pathways with near-term GHG emissions are projected in line with BC government policies implemented until the end of 2025 and extended with comparable ambition levels by 2030, and beyond. As illustrated in Fig. 10, the decline in carbon intensity resulted from the fast deployment of innovative and renewable technologies across BC's EITE industrial sectors. As per our technological roadmap Foundation-to-Action (Fig. 9), renewable hydrogen meets 15% of BC growth in electricity demand. Solar, wind, and hydrogen generation each increased in the mid-term by around 55%, helping to avoid over 3 Mt in EITE sectors' emissions. All pathways (Fig. 8 and 9) assume immediate action is taken. GHG emissions for 2018–2022 were used to project the outcomes shown in Fig. 10.

4. Discussion

Our recommended roadmap is challenging, requiring governments, businesses, and investors to take action every year so that BC's EITE industries achieve net-zero emissions by 2050. We advance climate policy analysis by better incorporating future estimated cost reductions on regional EITE sectors and we offer our recommendations through the lens of innovation management. Our recommended measures incentivize the development of key novel technologies, such as CCU/S, hydrogen, and digitalization, that have the potential to benefit leaders in R&D, as part of create new revenue models in industry. We recommend significantly increased investments in R&D activities related to innovative technologies and policies to incentivize support across new value streams to meet 2050 emissions targets, with the aim of fostering rapid emissions reduction potential, as suggested in our Fig. 9 technological roadmap. The deployment of key technologies hinges on economic cost but also on interactions between R&D leaders and policymakers, that may advise BC government officials, to offer investment incentives for emerging technology developers.

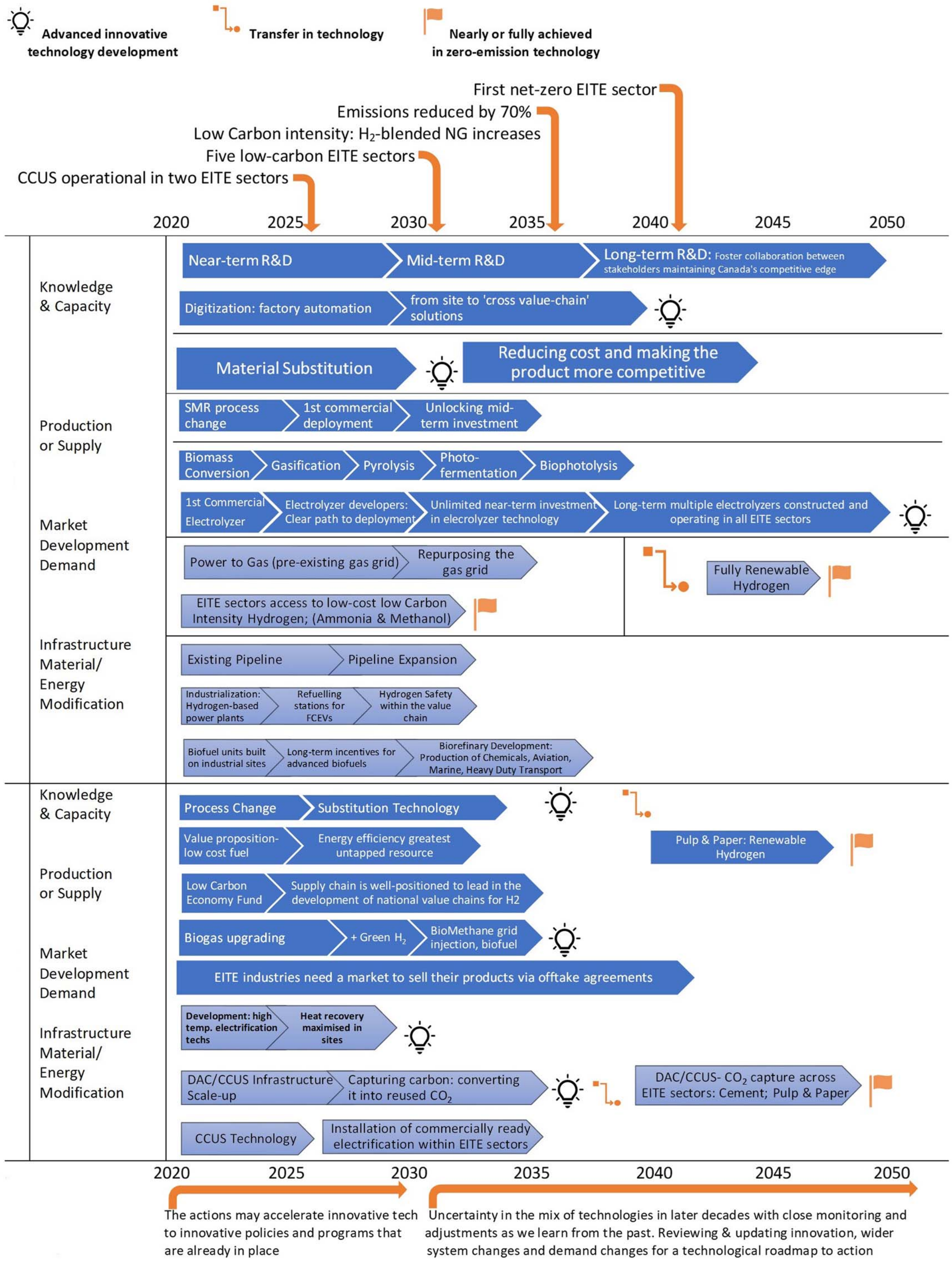

Fig. 9 The schematic for the "Roadmap Foundation-to-Action." Source: Authors' analysis.

From our roadmapping analysis, in Section 3.4 (Fig. 8 and 9), we found that securing investment revenues to be among the hardest components for EITE sectors, because project finances are rarely available to them. In our roadmap we also incorporated considerations for EITE industry infrastructure modifications that support the rapid adoption of on-site net-zero emission technologies across different EITE industrial sectors.

4.1. Innovation policy for BC's EITE industries

Innovation policies and industrial net-zero carbon strategies for any geographic region need to be designed considering the unique circumstances of each local economy and energy system. There is no uniform or all-purpose approach to clean energy transitions, and thus, policies need to reflect political and geographic regions at differing stages of economic

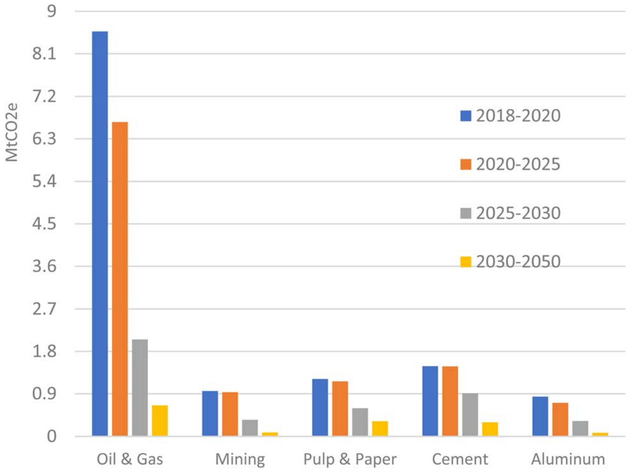

Fig. 10 2050 pathway: emissions reduction potential by major abatement by technological roadmap. Source: Authors' analysis based on data from CEEDC.

development. In Canada, the provinces are an appropriate regional entity on which to focus our analysis. The pathway in our roadmap is BC-focused[42] in scope. EITE industrial policy that aims to strengthen provincial industries has resurfaced as a strategic area for policymakers in response to the financial crisis that began a decade ago. In an industrial policy context, environmental and climate concerns are just one part of that response.[94]

Our analysis was informed by the International Energy Agency (IEA). As the world's leading energy authority, the IEA[36] is an authoritative resource providing governments with support and advice as they design and implement their roadmaps, and encouraging international cooperation across sectors to reach net-zero by 2050. Our analysis was also informed by innovation management literature, including technical economic analysis[108,109] and input from Canadian cleantech accelerator Foresight CAC, which has been bringing BC's leading industries and cleantech entrepreneurs together in a "Core Cluster" initiative.[42] A key component of Foresight CAC's Core Cluster innovation ecosystem framework is advising governments on policy-making.[52] Our research team is actively collaborating with Foresight CAC, PICS, and BC government policymakers in recommending policies and solutions that can reduce BC's industrial GHG emissions and sustainably generate economic prosperity in the province. The innovative technology potential solutions required to meet BC net-zero 2050 goals are identified as being in the early stages of development. This roadmapping analysis provides potential recommendations to inform policy and actions taken within a near-term timeframe of 2025–2030.[39,45,49,67,110,111]

4.2. Leading R&D laboratories in BC: a potential impact to the clean-energy transition

Innovative technologies developed in academic or industrial R&D laboratories are an essential component of the pathway to commercializing innovative technologies for EITE industries to achieve a clean-energy transition. However, the commercialization of laboratory-scale inventions from lab-scale processes to mass production and marketing is complicated by the gap in knowledge that exists for many science-based ventures.[50,65,112] Furthermore, as reported by Maine *et al.*,[40] significant capital costs are involved in full-scale prototype development for novel production processes and risks and uncertainties for early adopters. While cost modelling approaches can inform predictive linkages between R&D objectives and limitations, process conditions, financial assumptions, and cost estimates, they are limited to assessing a single technology. There is a need for integrative frameworks to guide commercialization decisions for lab-scale processes or to inform R&D priorities in the context of broader political and economic decision-making. To address this gap, we have incorporated decarbonization options from four categories of "Knowledge & Capacity," "Production or Supply," "Market Development Demand," and "Infrastructure Material/Energy Modification," shown in Fig. 8, for specific innovative technologies which are compatible with the EITE industrial sectors included in the roadmap. These considerations were used to select the innovative technologies shown in Fig. 9. Governments can intervene through the introduction of hydrogen and electrification policies and funding that helps to bridge the gap in the adoption of CCU/S technology that can be included in EITE industrial infrastructure and hardware modification, thereby enabling quicker adoption of innovative technologies by EITE industries. For example, BC's pulp and paper mills are ideally suited for hydrogen production from electrolysis, combining access to significant energy infrastructure. Locating electrolyzer projects onsite would provide an opportunity to foster near-term economics of hydrogen production.

4.3. Hydrogen production pathways and GHG emissions

As discussed earlier in Section 3.2., 'the competitive landscape in patent activity for hydrogen production,' the move towards a carbon-neutral electricity mix could potentially benefit hydrogen production across all EITE sectors in BC. Hydrogen can be produced with several production pathways broadly split into fossil fuels and renewables (S12 in ESI Material†).

To achieve a net-zero emission economy by 2050, BC energy sources for industries must be largely decarbonized. This could impact hydrogen production pathway emissions.[102] Most notably, electrolysis with grid electricity becomes viable compared to the 2030 global average grid mix, which remains carbon-intensive. Therefore, it has been included in Fig. 8 and 9.

Fig. 7 demonstrates electrolysis as the dominant green hydrogen production technology that existing companies are investing in patented research. While electrolysis needs further development regarding cost and implementation in most regions (the Hydrogen Council, published in January 2021 (ref. 113)), the case is much more compelling in BC due to the province's clean electricity grid.

Our analysis indicated that electrolysis + renewable electricity could potentially become viable compared to other production pathways by 2030. A cost comparison resulting from different methods of hydrogen production pathways is shown in Tables S8 to S11, in the ESI Materials.†[102] TRL level, capital cost, production cost, and efficiency are also indicated. (Data source: adopted by the authors from Ajo Joseph, Frost & Sullivan[55] and Abdin *et al.*[102]) To address the cost of hydrogen production, Tables S8–S11† provide information such as hydrogen cost and TRL level:

• Hydrogen storage: Energy Demand for Storing and Releasing Hydrogen, Global, 2020 (Table S8†).

• Hydrogen storage: Techno-economic Comparison of Liquefied Hydrogen Storage, Global, 2020 (Table S9†).

• Power-to-X technology: Technology Comparison, Global, 2020, 2020 (Table S10†).

• Alternative fuels production: Comparative Analysis, Global, 2019 (Table S11†).

The capital cost of green H_2 production through low-temperature PEM electrolysis is estimated at 800–1000 $ per kW, while the high-temperature electrolysis is over 1000 $ per kW. Given these assumptions, renewable hydrogen produced through electrolysis is forecast to cost $2 per kg by 2050.

4.4. The demand for proven, reliable, and flexible solutions

Along with developing longer-term innovative technologies, proven, reliable, and flexible solutions for decarbonization are required in the near and medium term. A growing need for flexible and dispatchable power sources has accompanied the increase in renewable energy production.[113] Ammonia could play an flexible energy carrier for hydrogen in EITE industries due to its energy density, its proven synthesis technology and existing supply chains[115] to drive decarbonization, as contemplated in the roadmap in Fig. 9. Fuel conversion to ammonia requires the modification of infrastructure hardware and safety control.[116] Infrastructure material and energy-modified control systems can be smoothly and securely upgraded, maintaining high reliability while achieving a fuel conversion that allows EITE industries one step closer to achieving decarbonization targets.

Operating and capital costs for hydrogen storage *via* ammonia is slightly lower than for liquid hydrogen (S9 in the ESI Material†),[17,117] and ammonia has a high hydrogen density, which leads to low fuel consumption during transportation. Ammonia has good potential as a hydrogen carrier suitable for large-scale storage and transport. However, due to insufficient technical maturity, ammonia cracking is the main obstacle to implementing the ammonia hydrogen storage cycle.[118,119] Thus, another alternative in BC is to produce methanol, allowing BC to become a significant methanol production centre that would be an excellent use of large quantities of green hydrogen. Therefore, it is contemplated in the Market Development Demand action line in Fig. 9.

Producing methanol from green hydrogen could potentially put an extra load on the electricity grid and is a constraint that must be considered. BC could potentially generate the electricity required for industrial quantities of green hydrogen[49] on top of all the electricity needed for industrial heat pumps and the other added loads of the future clean economy. This is an essential question since BC Hydro has predicted that in approximately ten years, BC will only be able to provide for some of the anticipated demand for electricity.[49]

Wind and solar may provide sufficient green and clean future energy. Still, there is no single set of solutions about what to do with this renewable energy when demand and supply are out of sync in time and location. A single-dimensional approach (*e.g.*, batteries alone or a renewable hydrogen economy) has a lower chance of success. Ammonia and hydrogen are two complementary zero-carbon fuels with good potential to replicate the immense fuel reserves and usage that fossil fuels provide us with today.[115] To spur industries to accelerate, Foresight CAC, PICS, and Simon Fraser University have provided programs as motivation and guidance.[1,42]

The leading decarbonizing technologies for producing hydrogen feedstock in ammonia/methanol are:

(1) Keeping steam methane reformed-produced hydrogen with natural gas as a feedstock, but adding CCU/S or carbon dioxide pyrolysis processes to produce solid carbon.

(2) Fuel switch to biomass-based hydrogen. Biomass is a possible scalable feedstock, *i.e.*, in the pulp and paper sector; or

(3) switch to green hydrogen electrolysis.

The experimentation with pilot projects and decisions to invest in any of these alternatives must be made in the context of constraints on clean electricity supply and prioritization of energy demand in BC. Thus, all these promising alternatives for decarbonizing EITE industries have been included in our customized technology roadmap, shown in Fig. 9.

4.5. Innovative technology: DAC and CCU/S, lithium battery-based energy storage

As part of the clean energy transition in BC, other innovative technologies to monitor and grow include DAC, CCU/S and Li-batteries. Carbon sequestration, as a means for BC EITE industries to reduce the effective carbon intensity of their operations, relies at least in part on CCU/S.[120] Many relevant technologies are being developed in BC-based R&D labs (Table S6 of the ESI Material†). However, the range of technologies at different TRLs still requires significant public and private investment and government interventions to accelerate adoption by EITE industries. Through the provision of funds as well as introducing policies and regulations to remove barriers to hydrogen production and adoption, both the provincial and federal governments can help with spurring the construction of CCU/S facilities at or near EITE industrial sites, as provided for in our roadmapping exercise in Fig. 9.

The facilities developed by Carbon Engineering captures CO_2 directly from the air and stores it safely, permanently, and securely underground in geological formations. With DAC, atmospheric CO_2 can also be used as a feedstock to create low-carbon products like plastics and concrete.[121] Carbon-capture technologies based in BC and Canada, categorized by technology and process type, description, state of development, GHG impact, energy impact, cost, and references are listed in S6 in the ESI Material.†

Decarbonizing emissions from process heat, for example, a total of 20 $MtCO_2e$ in the Aluminum industry at Rio Tinto in BC, can be a part of BC's solution. A low-carbon energy system could involve a possible combination of measures including a significant decarbonized heating process. To decarbonize heat, the BC government announced a policy to cap emissions from the gas distribution system, a mandate to require 100% efficient heating equipment in future sales, and an intention to support infrastructure electrification financially and institutionally.[4] If low-carbon fuel may not play a significant role in heat decarbonization, decision-makers might explore alternative applications for biomethane and hydrogen in other hard-to-abate sectors. It is reported by Stark *et al.*,[66] R&D in zero-carbon heat technologies is needed to increase attainable top temperatures, reduce capital costs, and in the case of solar thermal, increase resource dispatchability. This could achieve low cost, energy, and GHG emissions trade-offs of the various solutions with zero-carbon heat.

Electrification has significant potential as a world-leading strategy under varying stages of research from R&D labs to market and scale-up[85] contributing towards a 2050 net-zero emission target. Electrification is realized through the installation of industrial heat pumps and electric vehicle chargers., *i.e.* in the mining sector. Direct government financial support can also accelerate electrification. For example, the BC Government's CleanBC plan includes discounted industrial electricity rates with about $20 million in other incentives.[77] Increased operational efficiency of electrification is particularly advantageous in mining sectors that are difficult to decarbonize and where alternatives are limited. Advances in lithium batteries will decarbonize the mining sector for vehicle use underground and BC is already a leader in battery-electric technology for underground mining.[86]

5. Recommendation for implementation: roadmap foundation-to-action

Implementation plans should consider solutions for industry best practices, budgets, timelines, collaborators, and additional resources. Our approach is a well-implemented technological roadmapping exercise, where its foundation, described in Section 3.4, not only presents the technical issues but also starts a dialogue to facilitate EITE industrial actions. It provides the flexibility to develop an approach where energy solutions are to be balanced with economic cost of emissions abatement[122] and which facilitates coordination between government and business initiatives. The roadmap aims to reduce the risk for businesses by recommending investment in innovative low-carbon options, presenting expectations on what can and should be achieved from policy, and offering a framework of conditions necessary to make a transition to net-zero emissions.[94] The roadmap focuses on BC's EITE industries and hard-to-abate sectors, which are involved in metal and non-metal mining, smelting and refining, and the production of industrial goods, such as refined petroleum products, chemicals, aluminum, pulp and paper, and cement.[123,124]

Innovative technologies, such as electrification, replacing fossil fuels with sustainably produced biomass, and low carbon-intensity hydrogen, are available to decarbonize industry, and their adoption can be accelerated by innovation policy and climate policy. As different types of hydrogen production are not equal in achieving GHG emission targets by 2050, our technological roadmap provides recommendations to advance zero-carbon and renewable hydrogen pathways, with a particular focus on lowering the price of green electricity and thus leveraging hydropower in BC is critical to achieving this goal.[49] Nevertheless, despite low-to-zero carbon pathways for hydrogen production, adopting CCU/S technologies can be applied to other production pathways with regulated carbon-intensity limits to be established within the hydrogen value chain in the near and short-term.

5.1. R&D innovation: continuous actions independent of implementation timing

From our data gathering and roadmap creation we recommend that BC cleantech companies, investors, and governments, prioritize decarbonization and direct abatement above all other climate mitigation activities. R&D innovation action means getting as close to net-zero emissions as possible by 2030, and only then identify high-integrity ways to capture remaining emissions that are the most difficult, expensive, or technologically complex to abate by 2050. The key components projected from the near-to long-term, illustrated in Fig. 10, could only be achieved when strong cooperation between BC and Canada on clean energy R&D innovation is achieved. This requires significant, timely and purposeful government investment.[68] Recent investments from the US, the Netherlands, Japan, Germany, and the European Union are far higher and represent a threat to Canadian leadership in clean energy sectors. The following are the actions that are recommended from this analysis:

(1) R&D funding: align with net-zero targets prioritizing a strategic investment fund to support the below recommendations,[109,112,125] including BC's five EITE sectors, supporting the industry through establishing dedicated R&D funding and the challenges of modifying existing EITE infrastructures.[127,128] Examples include BC's renewable/net-zero emission energy program and federal funding through Natural Resources Canada (NRCan).

(2) Stimulate R&D interactions between different sectors within the value chain, and apply funding to overcome financial barriers to achieve feasibility demonstration and early-stage commercialization for innovative technologies with high unit costs.[8,128]

(3) Provide investment support and corporate tax provisions to aid private companies' R&D activities and capital costs, *i.e.* with government support, cleantech-based project funds annually to 2030.[129–131]

(4) Invest funds for cleantech-based projects with industrial infrastructure and energy-scale modification[126,127] to support heat decarbonization, including electrification, digitalization, and sustainability[86,132–134] of processing systems in EITE sectors to realize cost savings in industrial processes.[135,136]

(5) Modify EITE industry infrastructure with on-site net-zero emission technology to handle production and delivery, leading to a rapid momentum for innovative technologies in EITE sectors, supported across new value streams to meet net-zero targets.

(6) Targeted funding to fill knowledge gaps surrounding hydrogen or hydrogen-blended gas distribution and transmission to end-use applications.[15,106]

5.2. Near-term actions (2020–2025)

(7) Develop a green hydrogen market, with the majority of hydrogen supply produced using electrolysis from cheap grid electricity from, hydro, wind and solar renewables.[137,138]

(8) Require CCU/S deployment, reducing fossil fuels CO_2 emissions in 2025.[139,140]

(9) Develop a continuum of supports to bridge fundamental research to clean energy innovations that lower emissions and/or lower cost, including innovation training and fellowships for STEM researchers, de-risking supports, and pre- and post-venture formation commercialization supports.

(10) Update regulations and incentives for conventional gas-supply equipment for end-users of EITE industries to incentivize industrial building improvements and retrofits such as high-efficiency heat pumps.[33,59]

(11) Implement the 2023 Canada federal budget[96] supporting technology development and investment tax credits effective with a current annual investment of $15–25 billion[131]

(12) As per the 2023 Canadian federal budget, introduce a new refundable Clean Hydrogen Investment Tax Credit up to a maximum rate of 40% to attain net-zero emissions in Canada.[96] Verification of low carbon intensity claims might be necessary.

(13) Advance a coordinated strategy and roadmap for implementing CCU/S and negative emissions technologies in all difficult-to-abate industrial processes[16,140,141] through infrastructure modifications.[126,127,142]

5.3. Mid-term actions (2025–2030)

(14) For vehicle use in the mining sector and other industrial applications: increase the stringency of the federal Clean Fuel Standard and BC Low Carbon Fuel Standard by 2030.

(15) Blue hydrogen (fossil fuel-derived hydrogen with CCU/S) is forecast to lose its cost advantage relative to green hydrogen from electrolysis in the coming decade due to innovative support of hydrogen produced from electricity.[44]

(16) Commercial demonstration projects of low-carbon technologies should be fully developed and constructed. Such projects should focus on reductions in industrial process emissions using CCU/S and direct air capture, and implementing bioenergy and hydrogen applications in energy-intensive industries.[67]

(17) Electrification of mechanical and chemical processes, and zero emissions heating within the pulp and paper,[95] cement,[143] oil and gas,[100] mining,[68] aluminium,[82] and metal (*i.e.*, copper/lead/zinc) smelting sectors should be realized by 2030.[68]

(18) Ensure that major CCU/S projects in BC are scoped to reduce CO_2 emissions by >3 million tonnes annually by 2030 to achieve targets.[33,144]

(19) Support CCU/S projects to decarbonize methanol and ammonia production[145] and prepare processes to convert to green hydrogen when cost-competitive.

(20) Ensure that methane emissions from the oil and gas sector can be reduced by over 75% from 2020 to 2030.[54,146]

5.4. Long-term actions (2030–2050)

(21) Nearly eliminate all industrial methane emissions by 2035.[147]

(22) Implement technology requirement policies, zero-emission source building code materials for embodied emissions or technology standards-setting minimum requirements for energy efficiency, fuel economy, emission limits and carbon intensity by 2035.[148,149]

(23) Complete BC's entire decarbonization of the electricity sector by 2035 to enable net-zero emission electrification of industrial processes as applicable.[149]

(24) Realize full decarbonization of oil and gas, pulp and paper, mining and cement industries, where emissions associated with chemical processes that cannot be eliminated with existing or near commercialized technologies require far greater scaling of hydrogen, Li-batteries, CCU/S,[55] heat pumps,[150] and biofuels.[151]

(25) Realize full integration of net-zero emission hydrogen, ammonia, and methanol as energy carriers and industrial feedstocks, as a chemical feedstock for ammonia, methanol, food and drug production, as well as oil and gas sector processing used in crystal growth, glass manufacturing, chemical tracing, metal fabrication, polysilicon and semiconductor manufacturing, metal production, and thermal processing.[30]

(26) Support full electrification of hydrogen produced from renewables-based electrolysis by 2050.[108,152]

6. Conclusion

6.1. Summary of findings

By focusing on EITE industries in BC, we have investigated the potential for decarbonizing five sectors: oil and gas, pulp and paper, aluminium smelting, cement clinker manufacturing, and mining. Complementing BC's climate policies, we examined net-zero carbon technologies that these EITE industries could adopt to achieve decarbonization targets. An additional consideration was identifying innovation which could promote the development and growth of a low-carbon supply chain, BC's industrial competitiveness, and the scale-up of renewable companies and infrastructure. It was identified that multiple technology options including electrification, hydrogen, carbon capture and digitalization could play enabling roles in helping BC's EITE industries meet decarbonization targets in 2050. Identifying these relevant technologies for near-term or long-term implementation is important because they are considered important to achieving a net-zero GHG emissions target. Without considering the long-term goals, path-dependent decisions may undermine the region's and nation's environmental and economic goals.

To aid public and private sectors in striving for meaningful and clear pathways to decarbonization, we have developed a Technology Roadmap for BC to achieve climate targets in 2050 while enabling economic development. The need for more decarbonization technologies both provincially and globally is rising, and the need for efficient, reliable, and scalable production processes is a crucial factor. Although long-term demand for renewable hydrogen production and CCU/S technologies is apparent, an accelerated pathway to address this demand is needed by designing industrial technologies with low-cost processes, productivity, and facilitating market opportunities arising from the scale up of industrial processes for existing stakeholders within the value chain. BC companies and research institutes can potentially create a competitive advantage in utilizing green hydrogen technology. Our technology roadmap depicts how BC could develop this hydrogen sector to address environmental and economic goals. BC and Canadian government policymakers have an opportunity to shape the development of the future operations and supporting infrastructure of EITE industries to accelerate a transition to net-zero emissions and generate the foundation for a higher economic value proposition.

6.2. Limitations and opportunities for future research

There is an unavoidable degree of uncertainty when planning for a net zero energy system, as the Canadian Climate Institute states in their Net Zero Pathways[123] report: "Uncertainty and disagreement regarding the future shape of a net zero economy and energy system cannot justify delay". The key uncertainties when analysing energy systems include energy prices, technology prices, gross domestic product (GDP), population growth, and human preferences. Our study exhibited a number of limitations, and the results are subject to uncertainties. We did not use an energy-economy-emissions model in our analysis, nor did we calculated policy costs and thus were unable to directly compare the economic efficiency of alternative policy approaches.

Calculating emissions and costs for energy production presents a challenge for deciding how to account for the type of energy usage, technology, and products within our studied five EITE sectors. These detailed emissions, from each energy resource, were not extensively calculated in this study, given the varying stages of technology development and decarbonization policies and capacity change in EITE industries. For example, future research could include an additional sensitivity where the production costs of biomethane or hydrogen decline over time as technologies improve.

It was beyond the scope of this study to conduct a full sensitivity analysis on the many different parameters such as the emissions intensity and trade intensity of the five EITE industries studied. Future research could incorporate conducting a full energy-economy-emissions modelling analysis, which would assess key quantitative indicators such as the turnover rate of existing technology stock with zero-emissions alternatives, the cost of emissions abatement, changes to emissions and energy intensity of abating sectors, and the extent of trade exposure of EITE industries and the limits to emission abatement without the support of government policy. A full quantitative analysis would assess the impact of these aforementioned indicators with the implementation of different policy options in BC and Canada. While this study did not conduct a full energy-economy-modelling analysis, our research will enable future quantitative analysis by providing modellers with a timeline and development steps of technological innovation, expected uncertainties in the market adoption of zero-emissions technologies, and prescribed decarbonization trajectory necessary to attain GHG emissions targets while providing sufficient process and unit cost reductions to enable BC and Canadian EITE industrial firms to continue exporting globally. Furthermore, even without additional modelling analysis, the results of our work may be useful to policymakers planning for the clean energy transition and ensure that energy systems remain affordable and reliable amidst their decarbonization trajectory.

Nomenclature

AI	Artificial Intelligence
BAT	Best Available Technology
BC	British Columbia
CCU/S	Carbon Capture and Utilization/Storage
CICC	Canadian Institute for Climate Choice
CSPC	Canadian Science Policy Conference
CO_2	carbon dioxide
ECCC	Environmental and Climate Change Canada
EITE	Emissions-Intensive and Trade-Exposed
FBMR	The Fluidized Bed Membrane Reactor
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	The Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kg	kilogram
LNG	Liquefied Natural Gas
OECD	The Organisation for Economic Co-operation and Development
PV	photovoltaic
PEM	Proton Exchange Membrane
R&D	Research and Development
SCM	Supplementary Cementitious Materials
SDTC	Sustainable Development Technology Canada
SMR	Steam Methane Reforming
tCO_2e	tonne of CO_2 equivalent
Tcf	trillion cubic feet
TRL	Technology Readiness Level

Conflicts of interest

The authors declare there are no competing interests.

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