Supplementary material

S1 Cement sectors in BC, including technology or process type and name, description & solutions, state of development, GHG impact, energy impact, Cost, and reference type with its reference link. (PICS' research project: Technological Innovation and Climate Policy Solutions to Achieve Net-zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
Cement	Current Technology	Portland Cement	Calcium compounds, silica, alumina and iron oxide are placed in rotating kiln at 1500C.	Current Standard	0.5171 tCO_2/t of clinker	5.62 TJ/ t clinker			Canadian Industrial Energy End Use Data Analysis Centre (CIEEDAC). http://www.sfu.ca/cieedac.html
Cement			This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills				Uncertain	Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 Cement	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf
Cement -Lafarge Canada Inc. (Richmond)	to replace virgin aggregates with a recycled asphalt pavement (RAP) mix. One of several circular initiatives, the process of replacing virgin aggregates with recycled asphalt pavement significantly diminishes the depletion of natural resources and reduces carbon emissions while diverting truckloads of asphalt from landfills.	PHASE I — The Contaminant Program : Reduce harmful organic and inorganic substances, such as sulphur dioxide, dust and soot, as well as nitrogen oxides, from cement flue gas; • PHASE II — The CO_2 Capture Program: Separate the CO_2 from flue gas using a customized-forcement version of Inventys' carbon capture technology at pilot scale; • PHASE III — The CO_2 Reuse Program: Prepare post-combustion CO_2 for reuse and support the economical assessment and demonstration of CO_2 conversion technologies onsite, such as CO_2injected concrete and fly ash.	Solutions: 1. Biosolids to use as fuel in cement manufacturing at the Richmond plant.(received $753,000 in funding for the capital investment in a silo designed to co-process biosolids as low carbon fuel for the Richmond cement kiln. 2. Project CO2MENT (Flue gas from the plant's manufacturing facility is now captured through Svante's equipment – reducing the amount of gases released into the atmosphere. The system purifies the cement flue gas by trapping its contaminants to enable an efficient and durable CO_2 capture process. Now that Phase II is underway, Phase III - a demonstration of CO_2 utilization solutions such as reinjecting it into low-carbon fuels, CO_2 concrete, and fly ash – will begin in 2020.)	Pilot project (Inventys Partners with Total and Lafarge to Bring Carbon Capture Program to British Columbia)	Biosolids, when replacing coal, will reduce GHGs by approximately 5,000 tonnes of CO_2e per year	Along with carbon capture, the plant uses a $28-million system to use non-recyclable waste as fuel, directing it away from BC landfills.	Uncertain	Website report : https://www.lafarge.ca/en/inventys-partners-total-and-lafarge-bring-carbon-capture-program-british-columbia	https://www.lafarge.ca/en/project-co2ment
Cement - Lehigh Hanson Materials Ltd. (Delta)	Reducing the proportion of clinker is the most important level when it comes to minimizing energy consumption and CO_2 emissions		Solutions: 1. Development of alternative clinker 2. CCU/CCS. 3.Developing composite cements that contain less clinker.	the clinker proportaion in cement in 2019 is 74.5%	22% achived in 2019 and by 2030 will be -30%	-15%	kg CO_2 emission per tonne of cement in 2019, 589.8	Sustainability Report 2019 (page 35)	https://www.heidelbergcement.com/en/system/files_force/assets/document/93/63/heidelbergcement-sustainability-report-2019.pdf

S2 Pulp & Paper sectors in BC, including technology or process type, description & solutions, state of development, GHG impact, energy impact, cost, and reference type with its reference link. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
Domtar Inc.	Chemical Pulp Mills-The manufacturing of pulp and paper requires wood fiber, chemicals and energy	Chemical Pulp Mills- the conversion of Ashdown mill to 100% softwood and fluff pulp in early 2021. Airlaid and ultrathin laminated cores are highly customized with long and technical development, qualification and sales process.	Kamloops Mill (SFO), one line Fiberline Pulp Capacity and 408,000 ADMT (an air dry metric ton). The fiber used at Kamloops pulp mill is all softwood, originating mostly from third-party sawmill operations in the southern-interior part of British Columbia. The Company does not expect its facilities to be disproportionately affected by these measures compared to the other pulp and paper producers located in these provinces. (The province of Quebec has a greenhouse gases ("GHG") cap-and-trade system with reduction targets.)	Commercial. All of our pulp production capacity is located in the U.S. or in Canada, and we sell approximately 54% of our pulp to other countries.	Grand Total t CO_2e = 1327265.57	Energy sources include: biomass, natural gas and electricity. 73% of the total energy required to manufacture products comes from renewable fuels: bark and spent pulping liquor, generated as byproducts from our manufacturing processes. The remainder of the energy comes from smaller amounts of other fossil fuels and purchased steam procured under supply contracts.	British Columbia has a carbon tax that applies to the purchase of fossil fuels within the province.	ANNUAL REPORT FOR THE YEAR ENDED DEC. 31, 2020	https://www.domtar.com/sites/default/files/2021-03/0001564590-21-009629_0.pdf
Howe Sound Pulp & Paper Corporation	Kraft Digester, bleach plant and utility island• NBSK Pulp: 455,000 tonnes per year• Deep-sea port facility for economic access to Pacific Rim economies• Self-generated green power exported to BC's grid• Coastal BC fibre supply dominated by sawmill residual chips and pulp logs	Chemical Pulp Mills- The Paper Excellence Howe Sound Pulp and Paper facility is a leading producer of high quality Northern Bleached Softwood Kraft pulps.	ISO 14001 environmental management system certified91% of HSPP's energy comes from renewable sources with 46% reduction in greenhouse gases since 199092% of HSPP's power use is self-generated green electricity100% of HSPP's wood fibre is low risk using the FSC risk assessment processCertified to FSC Controlled Wood; FSC®, PEFC™ and SFI® Chain of Custody standards1.Strictest emission standards on the BC coast	Commercial.	Grand Total t CO_2e = 1446618			Fact Sheet 2020	https://paperexcellence.com/mill-location/howe-sound/
Canfor Pulp Ltd. Prince George Pulp and Paper-Intercontinental Pulp Mills	Enhanced - ECF Process-Chemical Pulp Mills. A sawmill energy modelling project was initiated that will ultimately have energy models developed for all of Canfor's B.C. sawmills in 2020, and will be able to account for the electricity savings made by individual projects. Biomass and clean electricity	SR: Using Technology to Enhance Operational Efficiencies Page 59, Sawmills - Greenhouse Gas Emissions Page 64, Pulp Mills - Greenhouse Gas Emissions Page 72. SR: Sawmills - Manufacturing Compliance Pages 68 - 70, Pulp Mills - Prince George Airshed Page 76. Canfor Pulp Sustainable Product Declaration Sheets	17 manufacturing facilities in BC. 4 pulp mills in British Columbia. Three of the pulp mills are in Prince George and produce premium reinforcing northern softwood kraft (NSK) pulp. WynnWood mill in British Columbia is certified to SFI CoC and will be transitioning to PEFC CoC in 2020. Programme for the Endorsement of Forest Certification (PEFC) chain of custody certification (CoC). Solutions: Sawmill energy consumption and carbon emissions: 1) To track electrical energy consumption.2) Use natural gas as an incremental heat source, rather than as a primary heat source in their kilns. 3) PULP MILL, BIOENERGY, BIOFUEL/PELLETS. Canfor has planted over 1 billion seedlings over 20 years, have high carbon sequestration properties	increasing kiln capacity at a number of operations, this causes an increase in energy consumption, specifically in natural gas and electricity.	Grand Total t CO_2e = 2118021 GHG emissions increased from 129 to 132 kilotonnes. sawmills reduced GHG emissions for diesel, gasoline, propane and biomass, overall GHG emissions increased by three kilotonnes (+2%) in 2019 due to increased natural gas consumption	behavioural changes, automating specific processes, and capital projects that have been shown to reduce energy consumption and lower energy costs. Canfor Pulp participated in the new CleanBC Industrial Incentive Program (CIIP), a Government of B.C.–led initiative that contributes to cleaner industrial operations across the province by reducing carbon tax costs for facilities that operate at or near world-leading emissions benchmarks. TCanfor continues to save 14,900 megawatthours of electricity annually, enough to power 1,040 homes each year.	facilitates emission reductions using revenues from the carbon tax that industry pays above $30 per tonne carbon dioxide equivalent.	2019 Sustainability Report CANFOR AND CANFOR PULP	https://www.canfor.com/docs/default-source/sr/canfor-and-canfor-pulp-sustainability-report.pdf?sfvrsn=40bee91_2
Canfor Pulp Ltd. Northwood Pulp Mill	Enhanced - ECF Process-Chemical Pulp Mills. A sawmill energy modelling project was initiated that will ultimately have energy models developed for all of Canfor's B.C. sawmills in 2020, and will be able to account for the	Product Description: 510,000 admt/yr Premium Bleached Softwood Kraft Pulp	100% of the fibre comes from non-controversial forests. 97% of the fibre is certified to sustainable forestry standards. Canfor Pulp has agreements in place with all our fibre suppliers to ensure that no protected or conservation areas are harvested. In addition, all of the harvested areas we source from have been assessed as low risk under the FSC Controlled Wood system.	All fibre is harvested from sustainable forestry operations in the Prince George region.	Grand Total t CO_2e =1487002	As described above (Canfor Pulp Ltd.- Prince George Pulp and Pape)	As described above (Canfor Pulp Ltd.- Prince George Pulp and Pape)	Northwood Pulp Mill Environmental Product Declaration Sheet 2020	https://www.canfor.com/docs/default-source/pulp/northwood_april2020_lr.pdf?sfvrsn=d714ee91_2

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	electricity, and Biomass								
Cariboo Pulp and Paper Company	Chemical Pulp Mills Acquisition of Peace River, Cariboo JV interest and Santanol in 2018 and Mercer Forestry Services in 2020 Ramp up of Friesau sawmill to capitalize on high-return opportunities and alternative market capability • Optimization of bio-extractives production	• 50% joint venture stake in reliable NBSK mill • Reliable wood supply sourced from large local sawmilling industry • Bio-mass fueled cogeneration power plant with two turbines; a 32 MW back pressure turbine to power pulp production and a 25 MW condensing turbine generator to generate electricity for sale to BCHydro	Location: Quesnel, British Columbia (~650 km north of Vancouver) • Pulp production capacity: 170,000 tonnes per year NBSK • Electricity generating capacity: 28.5 MW • Certification: ISO 9001 and ISO 14001 • 2020 green electricity sales: $5.4 million	Commercial	Grand Total t CO_2e = 1318150	170,000 tonnes NBSK 28.5 MW energy	Uncertain	Investor Presentation Report Feb. 2021	https://www.westfraser.com/responsibility/environment/air-ghgs
Catalyst Paper Corporation Powell River Division	West coast's largest specialty paper machines (2) • Deep-sea port facility with state-of-the-art power boiler and waste water treatment • Printing packaging papers: 334,000 tonnes per year • Coastal BC fibre supply dominated by sawmill residual chips and pulp logs • Self-generated green power export to BC's grid	Mechanical Pulp Mills The Paper Excellence Powell River mill is a leading producer of high quality newsprint and uncoated mechanical specialty papers.	ISO 14001 environmental management system certified • 93% of the mill's energy comes from renewable sources with 79% reduction in greenhouse gases since 1990 • 33% of their power use is self-generated green electricity • 100% of their wood fibre is low risk using the FSC risk assessment process • Certified to SFI Fibre Sourcing, FSC Controlled Wood; FSC®, PEFCTM and SFI® Chain of Custody	Commercial	Grand Total t CO_2e = 671467	under research	Less	Fact Sheet 2020	https://paperexcellence.com/mill-location/powell-river/
Catalyst Paper Corporation Crofton Division	Chemical Pulp Mills Catalyst Crofton Mill today has two paper machines and two pulp lines. Paper Excellence's Catalyst Crofton Mill is a combined pulp and paper operation.Coastal BC fibre supply dominated by sawmill residual chips and pulp logs	Its unique deep-sea port facility provides an economic gateway to major marketing in western North America, Asia and Latin America.	ISO 14001 environmental management system and ISO 50001 energy management system certified 87% of the mill's energy comes from renewable sources with 71% reduction in greenhouse gases since 1990 22% of their power use is self-generated green electricity 100% of their wood fibre is low risk using the FSC risk assessment process Certified to SFI Fibre Sourcing, FSC Controlled Wood; FSC®, PEFC™ and SFI® Chain of Custody standards1.	Commercial	Grand Total t CO_2e =1674233	under research	Uncertain	Fact Sheet 2020	https://paperexcellence.com/mill-location/crofton/
Catalyst Paper Corporation Port Alberni Division	Newsprint Mills- Catalyst Port Alberni Mill was the first British Columbia mill to integrate residuals from sawmills. Directory and coated papers: 336,000 tonnes per year• Coastal BC fibre supply dominated by sawmill residual chips and pulp logs	West coast's largest coated paper machine and uncoated groundwood paper machine• State-of-the-art mechanical pulping, utility island and waste water treatment	ISO 14001 environmental management system certified95% of the mill's energy comes from renewable sources with 83% reduction in greenhouse gases since 19909% of their power use is self-generated green electricity100% of their wood fibre is low risk using the FSC risk assessment processCertified to SFI Fibre Sourcing, FSC®, PEFC™ and SFI® Chain of Custody standards	Commercial	Grand Total t CO_2e =427714	under research	Uncertain	Fact Sheet 2020	https://paperexcellence.com/mill-location/port-alberni/
Skookumchuck Pulp Inc.	Chemical Pulp Mills Skookumchuck Pulp has seen substantial modernization work making the mill one of Paper Excellence's most sophisticated facilities.	The Paper Excellence Skookumchuck Pulp Mill Incorporated facility is a leading producer of high quality Northern Bleached Softwood Kraft pulps.	91% of the mill's energy comes from renewable sources with 69% reduction in greenhouse gases since 1990 77% of power use is self-generated green electricity 100% of wood fibre is low risk using the FSC risk assessment process Certified to FSC® and PEFC™ Chain of Custody	Commercial	Grand Total t CO_2e = 986342	under research	Uncertain	Fact Sheet 2020	https://paperexcellence.com/wp-content/uploads/2020/11/Skookumchuck-Pulp.pdf
Mackenzie Pulp Mill Corporation	Chemical Pulp Mills The company says all gaseous, liquid and solid chemicals, and residues have been safely removed from the Mackenzie mill site		The company says all gaseous, liquid and solid chemicals, and residues have been safely removed from the Mackenzie mill site.Paper Excellence Canada will be curtailing operations at its pulp mill in Mackenzie.MacKenzie Pulp Mill Corporation is located in Mackenzie, BC, Canada and is part of the Industrial Equipment Wholesalers Industry. MacKenzie Pulp Mill Corporation has 250 total employees across all of its locations and generates $121.93 million in sales (USD). (Sales figure is modelled). There are 45 companies in the MacKenzie Pulp Mill Corporation corporate family.	Commercial	Grand Total t CO_2e = 697670	under research	Uncertain	Jun/20	https://www.princegeorgecitizen.com/local-news/paper-excellence-closing-mackenzie-pulp-mill-3740617
Mercer Celgar Limited Partnership	Chemical Pulp Mills	Increased supply of spruce beetle damaged wood • Pine beetle and historic overcutting resulting in annual cut reductions across BC • Recent forest fires in Canada • Transportation bottlenecks	Sustainable products for a carbon conscious planet: Solid wood products produced from sustainably sourced, certified, private and public land suppliers – Products used in construction and renovation end uses – Displacing higher carbon footprint concrete and steel alternatives Pulp products produced from wood waste materials such as low quality forest wood and residuals from sawmills – End uses include bio-degradable tissue and packaging, as well as alternatives to plastic packaging. Electricity generated from the pulp chemical recovery process – Self-supply co-generated electricity and sell surplus – Green electricity capacity is displacing coal based electricity in most jurisdictions – Residual steam eliminates fossil fuel use Bio-based extractives produced from resins and natural oils of wood – Displacing hydrocarbon based products including food additives, aroma-therapy and fragrance applications	Commercial	Grand Total t CO_2e = 1330736	under research	Uncertain	Investor Presentation Report Feb. 2021	https://secureservercdn.net/198.71.233.72/4p3.786.myftpupload.com/wp-content/uploads/2021/03/2021-02-Raymond-James-Institutional-Investors-vFinal.pdf?time=1620583048
Nanaimo Forest Products Ltd.	Chemical Pulp Mills	In 2019 Harmac Pacific installed a Chlorine Dioxide (ClO_2) liquid containment and vapor suppression system. This system is designed to contain and prevent any large release of Chlorine Dioxide that would impact the surrounding environment.	The Harmac mill produces high quality kraft pulps made from custom blends of Douglas fir, western hemlock, balsam fir, interior SPF and western red cedar. With its strategic location on a deep water port, the mill is well situated for cost effective export of pulp and receipt of raw materials such as wood fiber. Harmac Pacific's propane is supplied by Superior Propane. Superior Propane provides the storage vessels fueling systems. Maintenance and servicing of this equipment is also provided by Superior Propane's service technicians.	Commercial	Grand Total t CO_2e = 1283000	under research	less	The company website	https://www.harmacpacific.com/environment.php
Celgar Mill	Chemical Pulp Mills These projects have helped to make Celgar a leader in the global pulp industry. The mill produces approximately 500,000 tonnes of Northern Bleached Softwood Kraft pulp, enough eco-certified green energy to supply our own needs plus up to an additional 20,000 homes and 250,000 litres of turpentine annually, making it one of the main employers and economic generators for the region. https://mercerint.com/operations/mercer-celgar/	Project Blue Goose, 2007 – a $24 million capital project improving operation efficiencies, increased production, and improved environmental performance. In 2019, we improved production by debottlenecking the pulp packaging line, as well as built a turpentine extraction plant to generate sales and reduce chemical costs.	• Location: Castlegar, BC, Canada (~600 km east of Vancouver) • Pulp production capacity: 520,000 tonnes per year NBSK • Electricity generating capacity: 100 MW • Certification: ISO 9001 and 14001 • 2020 green electricity sales: $10.9 million • 2020 bio-extractives sales: $0.06 million Green Energy Project, 2010 – a $61 million program that installed a second-turbine generator to increase the installed generating capacity from 48 MW to 100 MW, as well as upgraded the bark boiler and steam facilities.	Commercial	Grand Total t CO_2e = 1242048	520,000 tonnes NBSK 100 MW energy	less	Investor Presentation Report Feb. 2021	https://secureservercdn.net/198.71.233.72/4p3.786.myftpupload.com/wp-content/uploads/2021/03/2021-02-Raymond-James-Institutional-Investors-vFinal.pdf?time=1620583048

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Peace River	Harmac Pacific's propane is supplied by Superior Propane. Superior Propane provides the storage vessels fueling systems. Maintenance and servicing of this equipment is also provided by Superior Propane's service technicians.		• Growth in areas of core competence:• Acquisition of Peace River, Cariboo JV interest and Santanol in 2018and Mercer Forestry Services in 2020• Ramp up of Friesau sawmill to capitalize on high-return opportunities andalternative market capability• Optimization of bio-extractives production	Commercial	Grand Total t CO_2e = 140582	475,000 tonnes NBSK/NBHK70 MW energy	Uncertain	Investor Presentation Report Feb. 2021	https://secureservercdn.net/198.71.233.72/4p3.786.myftpupload.com/wp-content/uploads/2021/03/2021-02-Raymond-James-Institutional-Investors-vFinal.pdf?time=1620583048
West Fraser	• 100% Timber supply chain certified • 63.4 Million native tree seedlings planted in 2019 • 100% Harvest sites reforested • $12.3 Million invested to improve forestry and stewardship	West Fraser has invested in Low-Consistency Refining technology in our operations, reducing the electrical intensity in our BCTMP mills by 28% per ADMT (air-dried metric tonne) since 2005.	75% Renewable energy; 13% Reduction of GHG emissions in 2019; 9.4 Million tonnes of CO_2e stored in products; 99% of a log recovered for product, purpose or energy	Commercial	9.4 million CO_2e stored in long-lived wood products made in 2019	Electrical costs for mechanical pulping processes can make up as much as 35% of the manufacturing expenses for BCTMP pulp.	less	West Fraser 2019 Responsibility Report	https://www.westfraser.com/sites/default/files/sustainability/West%20Fraser%202019%20Responsibility%20Report%20Summary.pdf

S3 Aluminum sector in BC, including technology or process type and name, description & solutions, state of development, GHG impact, energy impact, Cost, and reference type with its reference link. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
Rio Tinto Alcan Inc. Mining located in Kitimat, British Columbia	Scope 3 goals are to: — Work in partnerships to develop breakthrough technology enabling the production of zero-carbon aluminium — Work in partnerships with customers on steel decarbonisation pathways and invest in technologies that could deliver reductions in steelmaking carbon intensity of at least 30% from 2030; — Work in partnerships to develop breakthrough technologies with potential to deliver carbon neutral steelmaking pathways by 2050 — Meet our ambition to reach net-zeroemissions from shipping of our products by 2050.	ELYSIS joint-venture with Alcoa achieved production of commercial grade zero-carbon aluminium and completed the construction of the first industrial pilot facility in Canada.	With clean hydropower facility at Kemano and the Nechako Reservoir, the Kitimat smelter produces aluminium with one of the lowest carbon footprints in the world. Page 5. Rio Tinto and Alcoa Corporation today announced a revolutionary process to make aluminium that produces oxygen and eliminates all direct greenhouse gas emissions from the traditional smelting process. (https://www.riotinto.com/en/news/releases/First-carbon-free-aluminium-smelting)	There are three main themes for the research that will be delivered through the C$1.5 million funding from NSERC	reducing the emissions intensity by 50%	under research	Since 2018, we have reduced Scope 1 and 2 emissions by 1.1Mt CO_2e, or 3%	RT-Climate report 2020	https://www.riotinto.com/en/sustainability/climate-change

S4 Mining sectors in BC, including technology or process type and name, description & solutions, state of development, GHG impact, energy impact, Cost, and reference type with its reference link. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
Mining BC			Coal mines emit Ventilation Air Methane (VAM) at concentrations of <2%. However these are significant source of emissions. This technology catalytically oxidizes methane before carbonating and calcinating in a fluidized bed. Essentially turning Methane into CO_2 and then capturing CO_2.			Energy used by the industry is estimated to be between 1.25% up to 11% of the world's total energy consumption, depending on source	Reduce the carbon intensity of our operations by 33% by 2030	Forsight website- Report	https://foresightcac.com/wp-content/uploads/2020/07/CCC-Mining_FinalDraft_09jul20.pdf
Teck Coal Limited	Bituminous Coal Mining-Elkview Operations	Teck has a 95% partnership interest in Elkview. Production 9.0 million of clean coal. Proven and probable reserves at Elkview are projected to support mining for a further 30 years.	using heat exchangers (by ethane combustion) to produce electricity. This resultes in a higher efficiency burning as well as turning a source of emissions into useful product.	Commercial, little penetration of electric vehicles in mining	Grand Total t CO_2e =458448	Uncertain	Reduce the carbon intensity of our operations by 33% by 2030	Teck website	https://www.teck.com/operations/canada/operations/elk-view/
Teck Coal Limited	Bituminous Coal Mining-Fording River Operations (FRO)	Targeting wash plant optimization in FRO—a key step in the steelmaking coal processing cycle—by creating an operator advisory tool that recommends ideal set points in the wash plant, based on an analysis of incoming material and historical data.	Improving productivity and efficiency through cutting-edge technology including: -Machine-learning predictive maintenance on mobile equipment -Mining analytics to improve haul cycle times -Processing improvements driven by artificial intelligence -Connecting data systems to improve blast and shovel performance	Commercial, little penetration of electric vehicles in mining	Grand Total t CO_2e =573128	Uncertain	Reduce the carbon intensity of our operations by 33% by 2030	Teck website	https://www.teck.com/operations/canada/operations/fording-river/
Teck Coal Limited	Bituminous Coal Mining-Greenhills Operations	the advanced sensing and analytics have also unlocked additional value, by identifying improvements to the thickener process, allowing the FRO wash plant to process additional coal from Greenhills Operations, thereby optimizing its processing capacity.	Reduce the carbon intensity of our operations by 33% by 2030 Procure 50% of our electricity demands from clean energy by 2025 and 100% by 2030 Accelerate the adoption of zero-emissions alternatives for transportation by displacing the equivalent of 1,000 internal combustion engine (ICE) vehicles by 2025 . 50% lower carbon intensity at our Fort Hills mine compared to US refined barrels of oil	Commercial, little penetration of electric vehicles in mining	Grand Total t CO_2e =408459	Uncertain	Reduce the carbon intensity of our operations by 33% by 2030	Teck website	https://www.teck.com/operations/canada/operations/greenhills/
Teck Coal Limited	Bituminous Coal Mining-Line Creek Operations	Line Creek produces steelmaking coal – also called metallurgical coal or coking coal — which is used to make steel. Also, involves the shipment of the steelmaking coal from the mine site to bulk port terminals in Vancouver by rail. It is then loaded on to larger seagoing vessels, which carry it to our target markets.	Teck operates the Highland Valley Copper mine in British Columbia.	Commercial, little penetration of electric equipment in mining	Grand Total t CO_2e =216720	Uncertain	Reduce the carbon intensity of our operations by 33% by 2030	Teck website	https://www.teck.com/operations/canada/operations/line-creek/

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S5 Oil & Gas sectors in BC, including technology or process type and name, description & solutions, state of development, GHG impact, energy impact, Cost, and reference type with its reference link. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
Parkland Refining (B.C.) Ltd.	Fluid Catalytic Cracking ("FCC")	Fluid Catalytic Cracking is the chemical process that utilizes a catalyst and heat to break long-chain hydrocarbons into shorter-chain hydrocarbons to produce gasoline, diesel and liquid petroleum gas.	Developing Parkland's overarching sustainability strategy and policy, as well as this inaugural report.from the Task Force on Climate-related Financial Disclosures (TCFD) and guid- ance from the Sustainability Accounting Standards Board (SASB) and the Global Reporting Index (GRI). CLIMATE CHANGE: Equivalent of 15,000 cars taken off the road through the production of renewable, low carbon fuels. Bio-feedstocks, such as tallow and canola, are considered carbon neutral feedstocks for the Burnaby Refinery and produce lower-carbon refined products. next Sustainability Report in the fourth quarter of 2021. Further to our commitment to lower-carbon leadership, on March 1, 2021 we launched a "carbon offset" reward option as part of our JOURNIETM Rewards program to help customers offset their emissions. These carbon offsets will be directed toward a landfill gas capture and utilization project in Niagara, Ontario.	A higher throughput indicates increased coprocessing and our continued development and advancement in lower-carbon-intensity fuels and technologies.	Grand Total t CO2e = 427960	greenhouse gas emissions reduction targets in next Sustainability Report in the fourth quarter of 2021	implementing a minimum of 70,000 metric tonnes of CO2e of emission reduction projects by 2025, electrification of the Dawson, Parkland, and Sunrise facilities	Sustainability Report, September 30, 2020	https://www.parkland.ca/application/files/4816/0149/4254/Parkland-Inaugural-Sustainability-Report-EN.pdf
ARC Resources	Conventional Oil and Gas Extraction	ARC's Dawson Phase III and IV facility was designed to be low emitting using waste heat recovery Has the capacity to reduce up to 78,000 tCO2e annually.	Carbon Pricing: ARC engages directly with the Alberta and British Columbia provincial governments and participates in discussions with representatives of federal and provincial governments through senior and working-level committees of the Canadian Association of Petroleum Producers on cost-effective emission reductions. ARC holds the position that federal and provincial carbon taxes and emission regulations must be implemented in a way that ensures reductions are meaningful, measurable, and cost effective while maintaining the competitiveness of the Canadian energy sector.	Improved engine efficiency is an opportunity for ARC to lower its cost structure through reducing overall fuel usage.	Grand Total t CO2e =359529	The new Dawson Phase IV facility integrates switchgear technology Enhances energy efficiency of gaspowered turbines and reduces emissions by 45,800 tCO2e annually	reduction in carbon tax obligation by $9 million annually by 2021 - substitution of hydroelectricity for natural gas used in power generation, revenue generation through the sale of carbon offsets, and reductions in operating costs	ESG Report, 2020	https://www.arcresources.com/assets/pdf/ARC-Resources-Ltd.-2020-ESG-Report.pdf
Canadian Natural Resources Limited	Conventional Oil and Gas Extraction	the acquisition, exploration, development, production, marketing and sale of crude oil, natural gas and NGLs. Page 11	As part of the Company's ongoing focus on technology and innovation and the reduction of its environmental footprint, the Company has previously implemented and continues to undertake projects such as: carbon capture,sequestration, storage and utilization projects, including reduction and capture of methane; CO2 capture from hydrogen plants; and research into the production of biofuel from algae. In addition, the Company installs renewable energy sources at remote locations, where appropriate. Page 11	may be, affected by political developments and by national, federal, provincial, and local laws and regulations such as restrictions on production, changes in taxes, royalties. amounts payable to governments or governmental agencies, price or gathering rate controls and environmental protection regulations.	Grand Total t CO2e =1124124	January 1, 2020, the CCIR was replaced with the Technology Innovation and Emissions Reduction Regulation ("TIER") Page 14	The BC gov. will be increasing the carbon tax at a rate of $5 per tonne of CO2e annually to $50 per tonne of CO2e on April 1, 2021. Page 15 Update: BC Carbon tax reach $50 on April 1, 2022	ANNUAL INFORMATION FORM FOR THE YEAR ENDED DECEMBER 31, 2019 published March 27, 2020	https://www.cnrl.com/upload/report/128/02/aif-march-27-2019.pdf
EnCana Corporation	Conventional Oil and Gas Extraction		Ovintiv Inc., formerly Encana Corporation, is a hydrocarbon exploration and production company organized in Delaware and headquartered in Denver, United States. It was founded and headquartered in Calgary, Alberta, and was the largest energy company and largest natural gas producer in Canada.		Grand Total t CO2e =987348			News	https://globalnews.ca/news/6459797/encana-completes-ovintiv-rebrand-denver-suttles-energy/
NorthRiver Midstream Inc.	Conventional Oil and Gas Extraction	NorthRiver is building a different energy infrastructure company, leveraging our assets and talented people to deliver new and innovative solutions for our customers.	NorthRiver Midstream is a Canadian gas gathering and processing business. With operations in British Columbia and Alberta, NorthRiver provides connectivity for its customers to major demand markets including the U.S. Pacific Northwest, U.S. Midwest and Western Canada.		Grand Total t CO2e =417803			website	https://www.nrm.ca/energy-done-differently/
PETRONAS Energy Canada Ltd.	Conventional Oil and Gas Extraction	Pacific NorthWest LNG was a liquefied natural gas export facility proposed to be situated on Lelu Island in the District of Port Edward, in northwest British Columbia. Pacific NorthWest LNG is majority-owned by PETRONAS	The company is currently drilling the fourth well on its first "start-up" pad and the second well is already faster than any of its other 600 Montney wells. Current net production is just under 70,000 boe/d and Petronas expects that to double to 140,000 boe/d over the next five years in a measured steady ramp up to an LNG Canada onstream date in 2023/2024. solutions: Develop low and zero carbon fuels, products and solutions. Advance emission reduction technologies such as carbon capture, utilisation and sequestration (CCUS) in high CO2 fields. Reduce hydrocarbon flaring & venting, capture methane emissions and optimise production and in operations. Mitigate GHG emissions from operations through energy efficiency improvement and use of low carbon or renewable energy. Minimise waste and promote recycling throughout the value chain. Increase efficacy in providing low carbon energy and solutions such as natural gas and renewable energy.		Grand Total t CO2e =543546	PETRONAS is pleased to announce that its wholly-owned entity, the North Montney LNG Limited Partnership ("NMLLP"), has entered into a Purchase and Sales Agreement for an equity position in the LNG Canada project in Kitimat, British Columbia, Canada.		website	https://www.petronas.com/sustainability/net-zero-carbon-emissions
Spectra Energy Transmission /Enbridge	Conventional Oil and Gas Extraction		all forms of energy—crude oil, natural gas, renewables—to meet rising global energy demand. As a company with both pipelines and wind turbines, Enbridge is delivering energy security and driving transformation toward a lower-carbon economy. We pay Carbon tax. Renewable Energy: more than $7.3 billion in capital to renewable energy and power transmission projects currently in operation or under construction. Our green energy portfolio includes 23 wind farms, 7 solar energy operations, 5 waste heat recovery facilities and 1 geothermal project, and we're expanding our presence in European offshore wind. Page 4		Grand Total t CO2e =2692139	5,080 MW GROSS 2,075 MW NET of zero emission energy generated (projects currently in operation or under construction)		Enbridge's economic impact on British Columbia	https://www.enbridge.com/~/media/Enb/Documents/Factsheets/ProvinceStateEconomicBenefits/2020BCEcoBen.pdf?la=en
Tourmaline Oil Corp	Conventional Oil and Gas Extraction	25% reduction in methane emissions by the end of 2023 based on 2018 figures • 25% reduction in corporate emissions intensity by the end of 2027 (scope 1) based on 2018 figures	Tourmaline is Canada's largest producer of natural gas, which is the cleanest hydrocarbon fuel.Tourmaline is also a member of the Natural Gas Innovation Fund (NGIF) allowing Tourmaline to participate in exciting R&D projects including GHGSat for using satellites to identify fugitive methane emissions in our British Columbia Montney Complex, Micro LNG which would allow off-grid (remote) communities the ability to use natural gas instead of diesel, Radmax Technologies that are building and testing a combined cycle device that would allow for zero methane well-sites by providing both electricity and compressed air for pneumatic controls, and many more exciting opportunities. Page 20		Grand Total t CO2e =427722	Created an internal Energy Efficiency Task Force to ensure Tourmaline is using the best technology to improve our emission footprint. 60 million tonnes reduction in global emissions per year.	9.8 million/annuall litres of diesel to be displaced ($11 million in savings per year). Reduction: ~30% CO2 emissions. ~75% NOX emissions ~99% SOX emissions. Page 26	The future is blue and green Sustainability Report 2019	https://tourmaline-sustainability.cdn.prismic.io/tourmaline-sustainability/23443923-4eb7-495f-b855-fd3f737c51d4_2019+Tourmaline+Sustainability+Report+Final.pdf

Supplementary material

S6 Carbon capture technologies based in BC and Canada, including technology or process type and name, description & solutions, state of development, GHG impact, energy impact, cost, and reference type with its reference link. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada)

Industry	Technology or process type	Technology or process name	Description and Solutions	State of development	GHG impact	Energy impact	Cost	Reference type	Reference links
CCS	Existing/under development	Existing/under development	This needs to be explored for each branch of industry, e.g. cement, steel, aluminium, refineries and future biorefineries	Parts are tested and proven but "systems" not, especially in an industrila setting	5 to 99% capture, all depends on choice of capture technology and scope of capture	Increases heat demand /or electricity demand (in case of oxy process)		UNIDO Roadmap & peer reviewed article	http://www.unido.org/environment/o591190/industrial-energy-efficiency/selected-projects/carbon-capture-and-storage-industrial-sector-roadmap.html
CCS	Existing/under development	Existing/under development	Review article on	Varying between R&D, pilot and commerical	5 to 99% capture, all depends on choice of capture technology and scope of capture	Increased energy deamdns for process	$10-$130/tonne CO2e avoided	Peer reviewed article	See Leeson, D., Fennell, P., Shah, N., Petit, C. & Mac Dowell, N. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries. International Journal of Greenhouse Gas Control In press, 71–84 (2017).
BECCS	New process		Capturing CO2 when producing e..g future biofuels in e.g. a gasificatiuon process minimizes the incrementalk cost for the "capture" (as CO2 already in high concentration)	Capture part no problem, success rests upon the gasification part	negative emission (up to 50% of carbon flow)			Research report - perr reviewed	http://portal.research.lu.se/portal/files/3340144/3363055.pdf http://www.ecn.nl/docs/library/report/2011/e11012.pdf
Terra CO2	New Process	Geopolymer	Geopolymer concrete combines an alkaline liquid with a geological source material containing silicon and aluminum to form a binder that does not use any Portland cement. Because the chemical reaction that takes place is a polymerization process, the material is called a geopolymer.	the State of the Geopolymer Research & Development	Resulting in CO2 emission reduction up to 80% compared with Portland cement	a reduction of 59% Energy needs in the manufacture of Rock-based geopolymer cement compared with Portland cement			http://www.geopolymer.org/wp-content/uploads/False-CO2-values.pdf
CarbonCure Technologies	Existing/under development	The production of geopolymer superior to all methods since it represents a high reduction in cost (Amran et al., 2020) and energy consumption (Voney et al., 2020), besides the added benefit of using industrialwastes to develop a different building material (Tong, 2020).	the mechanism of geopolymerization, including the controlling parameters and different raw materials (fly ash, kaolinite and metakaolin, slag, red mud, silica waste, heavy metals waste, and others) with particular focus on recent studies and challenges in this area. Developed a process for adding CO2 to ready-mix concrete in which the CO2 becomes converted into a mineral and sequestered to make a lighter, stronger and lower-carbon concrete. More than 100 concrete makers in the U.S., Canada and Malaysia are using the product.	incorporating nanotechnology in the production of geopolymer through nano-sized additives will yield good impact in reducing the cost and enhancing the mechanical properties.	Reduction in CO2 emissions has been measured up to 0.73 ton CO2/ton of OPC replaced by geopolymer (Dai et al., 2013).	Geopolymer can replace OPC, and thus decreasing the energy consumption, reducing the cost of the building materials, and minimizing the environmental impacts of the cement industry.	Searching for new activators is mandatory for lowering the cost at the large scale production and the sustainability	Peer reviewed article: Recent progress in environmentally friendly geopolymers	N. Shehata, E.T. Sayed and M.A. Abdelkareem, Science of the Total Environment 762 (2021) 143166
Mining and Carbon reduction	A UBC-based Tech. R&D	Carbon dioxide is removed from the gas before it exits the end of the pipe. The carbon is captured in the form of a solid mineral precipitate.	The carbon dioxide bearing bas is circulated through the pipeline containing reactive tailings. The Baptiste nickel deposit is ideal for a CO2 sequestration demonstration project. Prospects for CO2 mineralization and enhanced weathering of ultramafic mine tailings from the Baptiste nickel deposit in British Columbia.	BRIMM's Carbon Sequestration research project, led by BRIMM Director & UBC Prof. Greg Dipple	Direct air capture of CO2 would offset ~25% of a prospective mine's carbon emissions. Reaction of CO2-rich gases with tailings would offset ~50% of a mine's emissions.	under research	Potential savings would be $10.5 M/yr under a carbon price of $50/t CO2 equivalent.	Peer reviewed article	https://www-sciencedirect-com.proxy.lib.sfu.ca/science/article/pii/S1750583619302531
Low Carbon H2 production			The abundant natural gas resources could contribute to low-carbon hydrogen production if integrated with CCS facilities. The western Canadian sedimentary basins (WCSB)			R&D		Peer reviewed article	https://documentcloud.adobe.com/link/review?uri=urn:aaid:scds:US:f35cac97-39cc-4468-b64e-8609a6c901c1#pageNum=1
Carbon dioxide disposal	A permanent method of CO2 disposal based on combining CO2 chemically with abundant raw materials to form stable carbonate minerals. Preliminary investigations have been conducted on two types of processes, involving either direct carbonation of minerals at high temperature or processing in aqueous solution.	CO2 disposal in carbonate minerals	CCU has certain disadvantage: the requirement of high energy consumption processes such as mineral carbonation plus stable metal sources are required to fix CO2. In this work: concentrated seawater to supply metal ions. Plus, the selected 5 wt % amine solution changed CO2 into aqueous CO2 to reduce the additional energy required to form the metal carbonate under moderate conditions. As a result, precipitates were formed because of the reaction of carbonate radicals with metal ions in the seawater.	Varying between R&D, pilot and commerical	Zero	reduced in energy impact vs. CCU	uncertain	Peer reviewed article	https://dx.doi.org/10.3390/ijerph18010120
Canada three large-scale CCS projects	CCS offers a proven technology to reduce greenhouse gas emissions (GHG) in this hard to abate sector.	Post combustion flue gas is remarkably similar in cement or coal thermal plants and CCS lessons learned can be readily adapted and transferred across the industries.	1. SaskPower's CCS facility at the Boundary Dam Power Station near Estevan, Sask. 2. the Weyburn-Midale enhanced oil recovery projects operated by Cenovus Energy and Apache Canada 3. the Shell Quest project at the Scotford oilsands upgrader near Edmonton.	in commercial operation	Canada's renewed target aims to reduce emissions by 40 to 45 per cent below 2005 levels by the year 2030.	it would cost about 30 per cent less.	A second-generation BD3 - type project at double the size is projected to have costs 67 per cent lower per tonne of captured CO2 than the first.	Report by Beth (Hardy) Valiaho | Opinion | April 29th 2021	https://www.nationalobserver.com/2021/04/29/opinion/canada-must-go-big-carbon-capture-climate-goals
Carbon Capture-Next wave	Metal-organic frameworks (MOF). Chemically processing the fuel before it enters the power plant can turn it into CO2 and hydrogen. After the MOF captures the CO2, the hydrogen is burned, and the only byproduct is water. This extra chemical processing step would need to be built into new power plants as a pre-combustion process.	a class of highly absorbent, nanoporous materials called metal-organic frameworks (MOFs) have emerged as a promising material for carbon capture in power plants.	Snurr and his group have discovered a way to rapidly identify top candidates for carbon capture—using just one per cent of the computational effort that was previously required. By applying a genetic algorithm, they rapidly searched through a database of 55,000 MOFs.	R&D. Top candidate: a variant of NOTT-101, has a higher capacity for CO2 than any MOF reported in scientific literature for the relevant conditions.	10–15 per cent of power plant exhaust is CO2; the rest is mainly nitrogen and water vapor. Snurr and his team have designed a MOF that can sort these gases to capture CO2 before it enters the atmosphere.	under research	uncertain	Peer reviewed article, 2021	https://doi.org/10.1007/s10450-021-00314-y
Carbon Capture-Next wave	Nanosponges	consists of a silica scaffold, the sorbent support, with nanoscale pores for maximum surface area. They dip the scaffold into liquid amine, which soaks into the support like a sponge and partially hardens. The finished product is a stable, dry white powder that captures CO2 even in the	Emmanuel Giannelis (Cornell University materials scientists) have invented low-toxicity, highly effective carbon-trapping "sponges" that could improve carbon capture economics. that performs as well as or better than industry benchmarks for carbon capture.	R&D	uncertain	R&D	under research	website	https://www.engineering.cornell.edu/faculty-directory/emmanuel-p-giannelis

Supplementary material

		presence of moisture.							
Carbon Capture-Next wave	NH2-MIL-101(Al) metal-organic frameworks (MOFs) for CO2 separation.	Notably, the membrane containing 10 wt.% S-MIL-5 (NH2-MIL-101(Al) functionalized with 5.0 mL of APTES) showed an increment in CO2 permeability (50%), and ideal CO2/CH4 selectivity (80%) compared to the PES membrane	NH2-MIL-101(Al) metal-organic frameworks (MOFs) covered with 3-aminopropyltriethoxysilane (APTES) were incorporated into the polyethersulfone (PES) to produce mixed-matrix membranes (MMMs) for CO2 separation, developed at (University of British Columbia, Kelowna) for the first time, the ability to engineer dual transport pathways in MOF hybrid membranes by achieving very high loadings of MOF (50 wt%), which result in an 8-fold improvement in CO2 permeability from the pure polymer.	R&D	net carbon negative			Peer reviewed article, 2021	https://doi.org/10.1016/j.cherd.2021.09.011
Carbon Capture-Next wave	Crystals	a design of MOF at mesoporous SiO2 yolk-shell nanoreactors via a mesoporous silica coating followed by selective water-etching strategy. Different from conventional alkali- or acid etching methods, water etching of MOF surface presents a green and cost-effective way to form yolk-shell structures.	created crystals that capture CO2 much more efficiently than previously known materials, even in the presence of water. So far, this has been difficult since the presence of water prevents the adsorption of CO2. Complete dehydration is a costly process. Scientists have now created a stable and recyclable material where the micro-pores within the crystal have different adsorption sites for CO2 and water.	R&D	uncertain	under research	under research	Peer reviewed article, 2020	https://doi.org/10.1016/j.matt.2020.06.021
Carbon Capture-Next wave	Turning carbon to rock	the first time that CO2 can be permanently and rapidly locked away from the atmosphere by injecting it into volcanic bedrock. The CO2 reacts with the surrounding rock, forming environmentally benign minerals.	led by Columbia University, the University of Iceland, the University of Toulouse and Reykjavik Energy—has demonstrated that it can take as little as two years. CCS is currently happening at Reykjavik Energy's Hellisheiđi geothermal power plant	R&D- next step for CarbFix is to upscale CO2 storage in basalt. the CarbFix project, a European Commission– and Department of Energy–funded program to develop ways to store anthropogenic CO2 in basaltic rocks through field, laboratory and modelling studies.	between 95 and 98 per cent of the injected CO2 was mineralized over the period of less than two years, which is amazingly fast. up to 5,000 tonnes of CO2 per year are captured and stored in a basaltic reservoir.			Peer reviewed article, 2020	https://doi.org/10.1016/j.fuel.2020.117900
Carbon Capture-Next wave	Turning carbon into fuel	bubbled air through an aqueous solution of pentaethylenehexamine, adding a catalyst to encourage hydrogen to latch onto the CO2 under pressure. They then heated the solution, converting 79 per cent of the CO2 into methanol. Though mixed with water, the resulting methanol can be easily distilled,	Previous efforts have required a slower multistage process with the use of high temperatures and high concentrations of CO2, meaning that renewable energy sources would not be able to efficiently power the process. The new system operates at around 125–165 degrees Celsius, minimizing the decomposition of the catalyst, which occurs at 155 degrees Celsius. It also uses a homogeneous catalyst, making it a quicker "one-pot" process.	the process to the point that it could be scaled up for industrial use, though that may be five to 10 years away.		under research	uncertain	Patent	Conversion of carbon dioxide to methanol and/or dimethyl ether using bi-reforming of methane or natural gas, G. A. Olah and G. K. S. Prakash, U.S. Patent, 7,909,559, March 15, 2011., 2010-2011
Carbon Capture-Next wave	Turning carbon into fibres	Electrolytic production of iron in molten salts by splitting iron oxide into iron metal and O-2 is a low-carbon footprint alternative to the massive CO2 emissions associated with conventional carbothermal iron production and permits.	developed a technology to economically convert atmospheric CO2 directly into highly valued carbon nanofibres for industrial and consumer products, such as those used in the Boeing 787 Dreamliner, as well as in high-end sports equipment, wind turbine blades and a host of other products. it advances a CO2-free method for iron production, by modifying iron electrosynthesis in molten Li2CO3 to control iron product particle size and by decreasing the electrolyte extracted with the pure iron product.	scaling up quickly and soon should be in range of making t0nnes of kilograms of nanofibres an hour.		electrical energy costs of this "solar thermal electrochemical process" to be around $1,000/ton of carbon nanofibre product, which means the cost of running the system is hundreds of times less than the value of product output.	under research	Peer reviewed article, 2021	https://doi.org/10.1016/j.seppur.2020.117719
Svante	our technology captures carbon dioxide from flue gas, concentrates it, then releases it for safe storage or industrial use, all in 60 seconds.	using tailor-made nano-materials (solid adsorbents) with very high storage capacity for carbon dioxide. A sugar-cube sized quantity of our material has the surface area of a football field. We have engineered these adsorbents to catch and release CO_2 in less than 60 seconds, compared to hours for other technologies.	capture CO2 directly from industrial sources at less than half the capital cost of existing solutions, Svante makes commercial-scale carbon capture reality, and positions global industries to play offense in the fight against climate change.	market-ready and commercial-scale solutions. Follow a manual added link Pilot Plant 30 tpd, Lloydminster, SK, Canada. And LafargeHolcim Cement Pilot Plant 1 tpd Richmond, BC, Canada	400 Model – Pilot Plant 30 tonne per day (TPD) 1500 Model – Commercial Plant 500 - 1,000 TPD. 100 Model – Lab Testing Units 100 kg per day 200 Model – Field Testing Units 500 - 1,000 kg per day	A new class of materials such as functionalized-silica or metal-organic frameworks exhibit far sharper temperature and pressure swing absorption and desorption, which allow for lower parasitic energy loads and faster kinetic rates.		website	https://svanteinc.com/carbon-capture-technology/
Carbon Upcycling Tech (CUT)	The reactors are pressurized with CO2 from point source emissions. Then the material is treated through our patented Mechanically Assisted Chemical Exfoliation (MACE) process	We treat readily available powder feedstocks such as Fly Ash, crushed glass, steel slag, graphite, talc, and more	End Product: A suite of CO2 enhanced additives that are used in concrete, anti-corrosion coatings, plastics, consumer products, and more	scaling up - Eta: 20 tonne capacity	Compared to a conventional coating, CUT's anti-corrosion coating has a 87.5% lower carbon footprint. CUT's polymer additive can be incorporated into many types of polymers as a nucleator or filler but in Polyethylene, this additive results in a 90% lower carbon footprint.	CUT's technology is a low energy carbon utilization process which operates in batches so production is targeted at non-peak electricity hours.	New technologies are projecting a price of $58.30 per metric ton of CO2.	website	https://carbonupcycling.com/technology
Suncor Energy Inc.	At Suncor, we extract, produce and provide energy from a mix of sources, ranging from oil sands to wind and renewable fuels.	Carbon Capture	As Canada's leading integrated energy company, we embrace our role in shaping our shared and sustainable energy future and know that together we need to look beyond the energy needs of today and understand what is required for the future. Suncor pioneered oil sands development. Our early investments in technology helped unlock the potential of the oil sands by improving reliability and performance, expanding productivity and driving down costs while reducing our environmental footprint.	scale-up	the GHG intensity of cogeneration power is approximately 75 per cent lower than coal-fired power generation	R&D	under research		https://www.suncor.com
CleanO2	Calgary-based CleanO2 developed CARBiNX, a small-scale carboncapture device for home furnaces that captures CO2 in the form of carbonate, which can then be used to make a range of products, including hand soap.	Carbon Capture	"Environmentally friendly soap made with captured carbon. Every CleanO2 soap product is made with carbon that would otherwise have been released into the atmosphere if not captured by our CARBIN-X™ units and turned into amazing soap products that are great for your body, the community, and the environment. When you purchase CleanO2 soap products, you're supporting the deployment of more CARBIN-X™ units around the world to capture more carbon and reduce the impact on our climate.	under research		under research	uncertain	website	https://www.cleano2.ca/
CO2 Solutions Inc.	EXCLUSIVE PROPRIETARY HIGH-PERFORMANCE ENZYME: CO2 Solutions' innovative carbon-capture technology stands out through its ingenious use of the carbonic anhydrase (CA) enzyme.	Carbon Capture	CO2 Solutions Inc. developed an alternative to existing liquid amine carbon capture that produces no toxic waste. (Amine-based water-lean solvents are considered to be promising energy-saving alternatives to existing aqueous amine solvents for CO2 capture [https://doi.org/10.1016/j.cej.2020.125714]) The company has partnered with Resolute Forest Products to build a 30-tonne-per-day carbon-capture plant at the company's pulp mill in Saint-Félicien, with the CO2 to be used in the Toundra Greenhouse complex. CO2 Solutions' innovative carbon-capture technology stands out through its ingenious use of the carbonic anhydrase (CA) enzyme. Naturally present in humans and all living organisms, CA is vital to the organic exchange of CO2 during respiration. Heads turned in 2014 when CO2 Solutions presented their high-performance industrial version of carbonic anhydrase.	its commercial St-Félicien 30 tpd capture unit	2500 hours in order to capture ten tonnes of CO2/day.	under research	under research	website	https://co2solutions.com/en/history/

Supplementary material

Pond Technology	the world's first commercial installation to capture and convert industrial emissions into valuable nutraceutical end-products.	Carbon Capture	Developed a process for taking untreated emissions from power plants, refineries or cement plants and uses it to grow algae in bioreactors, sequestering the carbon and cleaning up other impurities from the exhaust. The algae is then used to make animal feed, cosmetics and biofuels. January 2018, Pond became a publicly-listed company, and in October 2018 broke ground on its first commercial-scale facility at Markham District Energy.	the world's first commercial installation to capture and convert industrial emissions into valuable nutraceutical end-products		under research	uncertain	website	https://www.pondtech.com/company/
C2CNT	Carbon Corp's C2CNT Genesis Device™ is a proprietary, revolutionary, new chemistry and technology introduced in 2015. In a manner similar to which aluminum metal is produced from aluminum oxide ore, by a process called electrolysis, Carbon Corp transforms Carbon Dioxide into valuable carbon nano materials by electrolysis.	Carbon Capture	The C2CNT's technology is delineated in our peer-reviewed technical publications and described in international media including the descriptions in the BBC, Forbes and Science. Carbon Corp uniquely directly removes and eliminates the greenhouse gas carbon dioxide from the atmosphere or from power plants, industrial processes, transportation and CO2 domestic sources. Instead of emitting carbon dioxide, Carbon Corp inexpensively produces carbon nanotubes (CNTs), carbon nano-onions (CNOs), or graphene, or ultra-strong carbon structural materials. With Carbon Corp, CO2 is intercepted directly from the atmosphere, or from flue stacks, without the need to concentrate the CO2, and split by electrolysis into O2 at the anode and into high value CNTs, formed by transition metal nucleation sites, at the cathode.	R&D	Carbon Corp, who relocated from the USA to Calgary, transforms CO2 into carbon nanotubes, with applications such as lightweight, ultra-strong and cost-effective replacements for metals; stronger cement-composite building materials; and expanding applications in industrial catalysis, batteries, and nano-electronics.	under research	uncertain	website	https://www.c2cnt.com
SeeO2 Energy	SeeO2 Energy converts CO2 emissions into high value fuels and chemicals in a net negative carbon process.	Carbon Conversion and Storage	This net negative carbon process can be used in green plastics, chemical and metal processing industries.	under research	net carbon negative	under research		website	https://www.seeo2energy.com/
Carbon Cap Inc.	The world's first industrial carbon recycling system.	Carbon Capture	Our patented TANDEM CARBON RECYCLING SYSTEM is housed in a modular, ontainerized drop-in unit, designed to capture and convert stack emissions directly at the source. Our proprietary process is net carbon negative, efficiently utilizing high volumes of heavy industry emissions – produced by power generation or other industrial processes such as cement and manufacturing – to create valuable materials and revenue streams.	under research	net carbon negative	under research	under research	website	https://www.sdtc.ca/en/companies/carbon cap-inc/
Hyperion Global Energy Inc.	All-in-One Capture + Conversion Drop-In System. INDUSTRIAL CARBON RECYCLING	Carbon Capture & Conversion	an Ottawa-based technology. Our patented TANDEM CARBON RECYCLING SYSTEM is housed in a modular, containerized drop-in unit, designed to capture and convert stack emissions directly at the source. Our proprietary process is net carbon negative, efficiently utilizing high volumes of heavy industry emissions – produced by power generation or other industrial processes such as cement and manufacturing – to create valuable materials and revenue streams.	scale-up	IMPACT: UP TO 99% CO2 MITIGATED AT SOURCE.	under research	under research	website	https://hyperionenergy.ca
CarbiCrete	With CarbiCrete, cement is replaced with steel slag, which is mixed with the other materials using standard equipment. The mix is then poured into a conventional block-making machine where the CMUs are formed.	Carbon Capture and cure	CarbiCrete is a Montreal-based carbon removal technology company that is developing innovative, low-cost building solutions that contribute to the reduction of greenhouse gas emissions. Carbicrete develops CO_2 mineralization systems that injects carbon dioxide into concrete for the construction industry. In order to cure the concrete, it must be placed into a specialized absorption chamber into which CO2 is injected. Within 24 hours, the concrete has reached full-strength.	scale-up	3kg. CO2 abated/removed per CMU. 500,000 Kg of CO2 permanently embedded in CMUs 1,000,000 Kg of CO2 emissions avoided	higher compressive strength by up to 30% and display better freeze/thaw resistance. Up to 30% Better compressive strength	10-20% Lower material costs	website	https://carbicrete.com

Supplementary material

S7 Cutting-edge innovative technologies within the hydrogen value chain from a) R&D Lab's universities in Vancouver and Victoria. (PICS's research project: Technological Innovation and Climate Policy Solutions to Achieve Net-Zero Emission by 2050 for EITE-Industries in BC and Canada) and b) Cleantech-based Companies. See profiles in the appendix for more details on these companies [1]

a)

Technology Developers	Transportation & Distribution	Utilities	End-use Applications
S. Holdcroft[2]	N. Branda [2]	M. Moallem	J. Axsen[2]
W. Merida[3]	K. Oldknow[2]	M. Adachi[2]	E. Maine[2]
B. Gates[2]	G. McTaggart-Cowan	J. Wang	M. Jaccard[2]
E. Kjeang[2]	M. Bahrami	K. Kavanagh	G. Wang
P. Palmer	F. Golnaraghi [2]	M. Ordoñez	J. Wang
D. P. Wilkinson[3]	P. Jula	W. G. Dunford[3]	Z. Dong
D. Harrington[4]	N. Djilali	C. Eskicioglu	R. Sadiq[3]
K. Smith	L. Li	Laboratory for Alternative Energy Conversion	J. Jatskevich
M. MacLachlan	G. Lovegrove	Institute for Integrated Energy Systems (IESVIC)	A. Lau
C. Berlinguette[3]	J. R. Martí		Sustainable Transportation Action Research Team
J. Zhang	J. Saddler[3]		
A. Rowe	P. Servati [3]		
J. R. Grace	H. Trajano		

b)

Technology Developers	Transportation & Distribution	Utilities	End-use Applications
☆BALLARD, LOOP, ☆AVL, Hydrogen In Motion, I:N:MR, ☆EKONA, GREENLIGHT INNOVATION, PROTON TECHNOLOGIES, ☆Cummins, ☆QUADROGEN, ☆Svante, ☆hydra, ☆xebec	Air Liquide, AIR PRODUCTS, HEXAGON, ZEN CLEAN ENERGY SOLUTIONS	FORTIS, BC Hydro, ATCO GROUP, TransCanada, AltaGas, ENMAX, TransAlta, ENBRIDGE	☆HTEC, ☆Powertech, HYUNDAI, TOYOTA

Supplementary material

S8 Hydrogen Storage: Energy demand for storing and releasing hydrogen, Global, 2020.

Source: Adopted by the author from the report called "Disruptive Innovations in Production, Storage, and Transportation of Hydrogen" with permission from Ajo Joseph, Frost & Sullivan [5]

Technology		Energy Demand of Energy Conversion Processes, kW/kg Delivered H2		Operating Costs of Energy Conversion Processes, $/kg Delivered H2			Technology Readiness Level (TRL)			
		Electrical energy	Thermal energy (heat)	Electrical energy, ≈ 0.15* $/kWh	Thermal energy, ≈ 0.04* $/kWh	Total	Conversion to storage carrier	Transportation	Process for releasing hydrogen	Total
Physical-based	Compressed gas	1-2 kWh_{el}/kg	-	0.3 $/kg	-	0.3 $/kg	9	8	8	8
	Liquid H_2 [6]	8 kWh_{el}/kg	-	1.2 $/kg	-	1.2 $/kg	7	7	6	6
Material-based	Adsorption	6-7 kWh_{el}/kg	-	0.9-1.1 $/kg	-	0.9-1.1 $/kg	4	5	3	3
	Metal hydride	10 kWh_{el}/kg	10 kWh_h/kg	1.5 $/kg	0.4 $/kg	1.9 $/kg	5	4	5	4
	Inter-metallic hydride	0.8 kWh_{el}/kg	2-6 kWh_h/kg	0.1 $/kg	0.3 $/kg	0.4 $/kg	3	3	3	3
	Complex hydride	1 kWh_{el}/kg	5-7 kWh_h/kg	0.2 $/kg	0.3 $/kg	0.5 $/kg	3	3	3	3
	Chemical hydrogen	2-6 kWh_{el}/kg	4-7 kWh_h/kg	0.3-0.9 $/kg	0.3 $/kg	0.6-1.2 $/kg	9	9	6	6
	Liquid organic hydrogen	2-3 kWh_{el}/kg	11-35 kWh_h/kg	0.3-0.5 $/kg	0.5-1.4 $/kg	0.8-1.9 $/kg	5	6	7	5

S9 Hydrogen Storage: Techno-economic Comparison of Liquefied Hydrogen Storage, Global, 2020

Source: Adopted by the author from a report called "Disruptive Innovations in Production, Storage, and Transportation of Hydrogen" with permission from Ajo Joseph, Frost & Sullivan[5]

	Hydrogen Storage densities		Technology Maturity	Energy Conversion Efficiency (%)	Operating Costs, $/kg delivered H2	Capital Cost, $/kg delivered H2	Delivery Cost, $/kg delivered H2
	Volumetric (kg/m3)	Gravimetric (wt%)					
Liquid H_2 [5]	70	-	6	37.1	1.2	1.8	0.6
Chemical H_2-ammonia [7]	123	17.7	6	36.9	1.1	1.6	0.3
Liquid organic H_2 [8]	57-64	6.2	5	24.7	1.9	3	0.8

Supplementary material

S10 Power-to-H_2 Technology: Technology Comparison, Global, 2020.

Source: Adopted by the author from the report called "Techno-economic Comparison of Power-to-X Technology" with permission from Ajo Joseph, Frost & Sullivan[5] (Techno-economic Comparison of Power-to-X Technology) **S11** Renewable hydrogen production via electrolysis: Innovation Technology from demonstration-R&D Lab to mature-commercialized [9]

Electrolyzers	AEC - Mature	PEMEC - Commercial	SOEC - Demonstration to R&D
Electrolyte	Aq. potassium hydroxide (KOH) [10]	Polymer membrane [11,12]	Yttria stabilised Zirconia (YSZ) [13]
Cathode	Ni, Ni-Mo alloys [14,15]	Pt, Pt-Pd [16]	Ni/YSZ [13]
Anode	Ni, Ni-Co alloys [17]	RuO2, IrO2 [18]	LSMb/YSZ [19] Ce/Ru [20] Ce/Ni [21]
Cell voltage (V)	1.8-2.4 [22]	1.8-2.2 [23]	0.7-1.5 [24]
Current density (A /cm2)	0.2-0.4 [25]	0.6- 2.0 [26,27]	0.3-2.0 [28]
Voltage efficiency (%HHV)	62- 82 [29]	67-82 [30]	< 110 [31]
Cell area (m2)	< 4 [32]	< 0.3 [33]	< 0.01 [13]
Operating Temp. (°C)	60-80 [10,25]	50-80 [34,27]	650-1000 [35,36]
Operating Pressure (bar)	< 30 [37]	<200 [38]	<25 [39]
Production Rate (m3 H2/ h)	< 760 [40,41]	< 40 [42]	<40 [32]
Stack energy (kWh / m3 H2)	4.2 -5.9 [43]	4.2- 5.5 [44,45]	> 3.2 [35]
System energy (kW /m3 H2)	4.5-6.6 [46]	4.2-6.6 [47,27]	> 3.7 (> 4.7)kWh-energy [48]
Capital Cost ($/kW)	1300 – 1560 [49]	2400- 3000 [50]	> 2600[51]
Stack Lifetime (h)	60,000- 90,000 [52,53]	20,000- 60,000 [44]	< 10,000 [54]

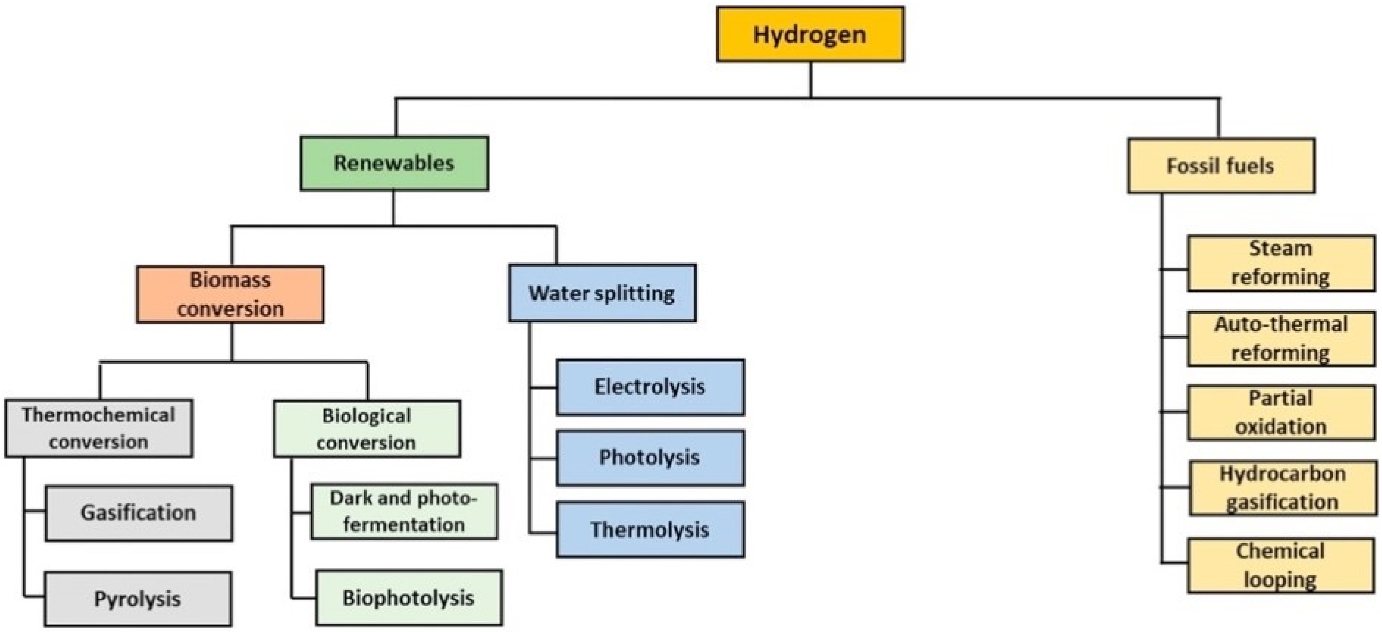
Supplementary material

S11 Alternative Fuels Production: Comparative Analysis, Global, 2019.
Source: Adapted by the author from the report "Breakthrough Technologies Advancing the Future of Alternative Fuels Production" with permission from Ajo Joseph, Frost & Sullivan [5]

Technology		**Technology Readiness Level (TRL)**	**Capital Cost**	**Production Cost**		**Efficiency, %**	**Cost efficiency**
				Hydrogen	Biofuel		
Thermochemical and Chemical	Pyrolysis	8	$50 – 650M	1 -2.5 $/kg	20-30 $/GJ	35-50	Medium
	Gasification	9	$115 – 150M	1.5-2 $/kg	15-60/GJ	40-50	High
	Hydrothermal Liquefaction	7	$100-125M	-	20-30 $/GJ	20–60	Medium
	Torrefaction	7	$10-20M	-	42 $/t	-	High
	Esterification	9	$375M	-	20-30 $/GJ	40-70	Medium
Electrolysis	Low-temperature Electrolysis	8	800-1000 $/kW	12-55 $/kg	-	40-80	High
	High- temperature Electrolysis	5	>1000 $/kW	2-11 $/kg	-	20-45	High
	Photo-electrolysis	5	-	10 $/kg	-	0.06	Low
	Microbial Electrolysis	6	1300 $/m3	3 $/kg	-	60-80	High

S12 Hydrogen production pathways via renewables and fossil fuels.[55]
Image source: Adapted by the authors from "Energy Transition Outlook" DNV.

Supplementary material



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