The potential to decarbonize Canadian heavy industry:

Technological and policy pathways
for Canadian energy intense industry
to thrive in a low carbon world

DRAFT V.3

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Please contact Chris Bataille (cbatailll@gmail.com) for more information about participating in sharing, expanding and curating the attached database for the *Global Heavy Industry Decarbonization Technology Database Project*

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Executive Summary

Maintaining a maximum increase in global temperature of 1.5-2°C will involve halving current global greenhouse gas (GHG) emissions by 2050 and reducing them to net zero by 2075, while still allowing for the production of materials needed to support global development. Much of the global climate policy effort has been on decarbonization of electricity and transport, however, and even in a net-zero carbon future firms and households will continue to need the material "stuff" of modern life. This includes traditional commodities like pulp and paper, mined minerals, iron, steel, chemicals, lime and cement, as well as potential new bulk commodities like biogases and liquids, hydrogen and synthetic hydrocarbon gases and liquids.

While existing Canadian heavy industry still relies on fossil fuel combustion, many have moved to lower intensity fossil fuels or renewable fuels in the past two decades as the capital stock has turned over. The pulp and paper industry has gone from a 100% fossil mix of oil and gas to less than 25% fossil (mainly gas) with 75% coming from biomass. The Canadian petrochemical sector has in large part switched from oil as primary feed-stock to natural gas, while international competitors continue to use oil. Nickel mining in Canada has less than half the emissions of international competition. Many of the older facilities face the challenge of capital stock turnover in a highly competitive marketplace. Notwithstanding the short term competitive issues that need to be recognized and managed, in the long run when the world eventually puts a price on carbon, Canadian producers could have a significant competitive advantage due to large biomass feedstocks and existing and potential supply of decarbonized electricity (and hence hydrogen or synthetic hydrocarbon sourced net zero emission liquids and gases) via hydropower, wind and solar, and a very large potential for geologic carbon capture and storage. This makes it an opportune place for decarbonized heavy industry.

The federal and provincial governments need to recognize the economic advantage of retaining heavy industry in a net-zero carbon world, and create a policy framework that enables industry to manage the transition to non-emitting operations without stranding assets or losing competitiveness. Resource production moving offshore, besides the lost employment and tax revenues, will in many case lead to carbon leakage and may thus be counted an economic and climate policy failure. In this paper we summarize global progress in understanding how to decarbonize heavy industry and identify the technical potential for decarbonisation of heavy industry. We also provide a summary database of heavy industry decarbonization technologies based on review of public literature; proprietary firm knowledge can be expected be much larger. The purpose of this report and database is to provide the basis for a long term vision for decarbonizing the heavy industry in Canada instead of forcing production offshore by demonstrating technically viable options to reduce emissions. Based on literature review, our findings identify that:

- the technical potential exists for decarbonizing GHG intense industry (Cement, Glass, Iron and Steel, Metal Processing, Mining, Refineries, Chemicals, and Pulp & Paper) within 1-2 capital investment cycles
- economically feasible potential will need higher granularity and more in depth understanding of the current technology and capital stock in place, and the relative cost in Canada vs. decarbonized industry in competitor jurisdictions.

Our recommendations:

- Make development of economically appropriate decarbonized heavy industry an explicit national and provincial priority.
- Implement a consistent policy and especially carbon pricing signal to industry to reduce GHG emissions to net-zero within 1-2 capital investment cycles without unduly hurting competitiveness for existing facilities (i.e. avoiding sunk costs and stranded assets, and the associated unemployment and social trauma).
- Participate closely and carefully in international negotiations related to trade in GHG intense goods. Ensure they send a clear signal for decarbonization of new stock while fairly protecting existing stock through the end of its life.
- Gather and harness the capacity of all the interested actors (industry, federal and provincial policy makers, academia, civil society, ENGOs) to develop a granular vision for long term decarbonization that 1) takes advantage of the research capability in Canada, 2) reflects appropriate capital investment cycles, and 3) identifies policy options to implement this vision.
- Participate in global R&D efforts for key industries not generally supported, and find partners with similar challenges (e.g. Australia, Russia).
- Identify economic and feasible decarbonisation pathways for heavy industry based on regionally specific circumstances, i.e. reflecting access to decarbonized electricity and geological storage for carbon dioxide.
- Establish provincial and federal institutions to coordinate and direct public research, technology dissemination and commercialization, and associated labour force training.

CONTENTS

1 INTRODUCTION

Global greenhouse gas (GHG) and specifically CO_2 emissions associated with fossil fuel combustion have been rising steadily since the early 1800s, but at an especially fast rate since 2000[1]. The global average temperature has already risen almost 1°C due to human emissions since the pre-industrial era. If not moderated soon, trends in global CO_2 emissions imply global temperature increases of 4°C or more by 2100[23]. To ensure a better than even chance of limiting this rise and the associated damages to +2°C, as agreed in the COP21 Paris Agreement, the International Panel on Climate Change (IPCC)[4], which gathers and synthesizes high quality peer reviewed scientific evidence on climate change science and economics, finds that global annual emissions must be reduced 42-57% by 2050 (relative to 2010), and 73-107% by 2100.

Canada has reversed its previously lukewarm commitment to climate policy, as evidenced by the recent joint agreement between Canada, the US and Mexico, wherein these countries' leaders committed to 50% clean electricity by 2025, a 45% reduction in methane emissions, and alignment of light and heavy duty fuel efficiency and GHG emission standards by 2025 and 2027, respectively[5]. Ontario, Québec, and Alberta all either have (Alberta's Specified Gas Emitter Framework has been in place since 2007) or plan some form of carbon pricing that puts a price on combustion, process and fugitive emissions, while BC has been taxing combustion emissions since 2007.[6] There are federal regulations banning new coal use for electricity generation, and at time of writing the Canadian federal government has entered into discussions with all provinces on the scope and type of some sort of minimum national carbon price. *Policy to limit GHG emissions has become the norm in Canada and should be expected to broaden and strengthen.*

Reducing global emissions by half by 2050 and zero by 2100 implies global per capita GHG emissions of less than 2 tonnes per capita by 2050 to allow room for basic needs in the developing world[7]. Canada currently emits 18 tonnes per capita[8]. While politically challenging, it has been repeatedly shown to be technically and economically feasible, most recently in the 2015 Deep Decarbonization Pathways Project[9], of which the author of this report was the lead author of the Canadian chapter. Most of these reductions are from efficiency, decarbonization of energy carriers (electricity and combustible liquids and gases), and switching to them from standard fossil fuels, as well as carbon capture utilization and storage (CCUS). A significant and repeated finding of the study, however, was the difficulty and cost of decarbonizing heavy industry due to its heterogeneity, GHG intensity, sensitivity to costs, and long lived production facilities. This entails special challenges for typically older Canadian heavy industry, dependent on process heat currently derived from combusting coal and natural gas.

On the demand side, however, global growth in consumption and replacement of existing stock of mined minerals, steel, cement, chemicals, cement and glass is such that even with a ~50% reduction in material used for most goods, building and infrastructure, we will still need a large and growing amount of currently GHG intense commodities[10]. There will also be new heavy industry in a global low carbon economy, including possibly hydrogen, biofuels, polygeneration of electricity and chemicals, and synthetic gas production facilities. Given a global move to decarbonization, a key strategic question for Canada's industry is will these traditional and new economy heavy industry facilities be sited in Canada, or will we import these commodities from other countries' decarbonized industry? Given the knowledge gap identified in IPCC (2014)[11,12] and the generally acknowledged lack of knowledge surrounding decarbonization of heavy industry[13], this report attempts to begin to address these questions from a practical heavy industry stakeholder perspective, informed from the academic and trade literature.

1.1 RESEARCH QUESTIONS & METHODS

Can heavy industry continue to operate and grow in Ontario and Québec, and more generally Canada, in a world committed to decarbonizing? This briefing report explores the implications of decarbonization for Canadian non-fossil fuel extraction heavy industry, and options for adaptation. We address ourselves to the following energy and emissions intensive industries: Cement, Glass, Iron and Steel, Metal processing, Mining, Refineries, Chemicals, and Pulp & Paper.

- **Core question: What options exist to decarbonize heavy industry?** Are there new build and retrofit pathways for the existing industries to continue operating, e.g. by dramatically reducing carbon (e.g. through efficiency, process electrification, decarbonized synthetic NG, or CCUS). We address this by conducting a survey of defensible heavy industry decarbonization technologies and processes via the academic and trade literatures. To prevent the exercise from descending into science fiction, we confined ourselves to the peer reviewed academic and trade articles, and websites based on them. This limitation put one layer of quality control on the exercise, but may also limit the scope of reasonable possibility (e.g. light emitting diodes (LEDS) were not imagined as a reasonable replacement for incandescent lights in 1980).
- **Secondary question: What are the relative competitiveness implications?** Processes and technologies to decarbonize heavy industry will have production cost and resulting demand implications. Trade rules, however, require that there be a level playing field in terms of climate policy, or one party or the other can impose carbon based import tariffs (i.e. countries cannot imposes tariffs over and above domestic regulation). The question then becomes not "How does decarbonization increase the cost of Canadian heavy industry" but "How does decarbonization affect the relative competitiveness of Canadian heavy industry?"
- **Secondary question: What positive approaches have other countries, regions, companies or institutions taken to these challenges?** Where appropriate, we describe

existing industrial applications that are focussed primarily on reducing GHG emissions, as well as processes or institutions that are tacking the challenge.

- **Secondary Question: How can we manage the transition from today's fossil fuel orientated industry to a net-zero carbon future without stranding assets, or harming competitiveness?**

The purpose of this study is an initial scoping survey, is opportunity seeking, and is not meant to be exhaustive, which would require another scale of resources.

1.2 STRUCTURE OF THIS REPORT

The structure of this report is as follows. Section 2 synthesizes our review of the broader literature on the technical potential for heavy industry decarbonization. Section 3 summarizes the sector by sector process and technological findings in the accumulated database. Section 4 discusses the implications of our findings and makes suggestions for further research.

2 LITERATURE REVIEW

Until recently analysis of heavy industry energy use was confined mostly to energy efficiency, not GHG reduction. The International Energy Agency[14] estimates that the implementation of current best available technologies (BATs) globally could reduce industrial overall energy consumption by 20% from current levels by 2050. On the other hand, industry-specific studies suggest that broad application of BAT could reduce energy intensity by about 25%, while innovation could deliver further reductions of 20% before approaching technological limits in some energy intensive industries[15].

The IPCC Fifth Assessment Report[16] provides the most recent comprehensive review of GHG mitigation options in industry. These include materials efficiency, energy efficiency, fuel shifts from coal to gas, carbon capture utilization and storage (CCUS), as well as decarbonisation of electricity supply to reduce indirect emissions. According to the IPCC, integrated models analysing all end use sectors and their interdependencies[17] point towards possible reductions in industrial final energy compared to baseline of 22-38%, and find that the potential for switching to lower carbon fuels, including electricity, heat, hydrogen and bioenergy ranges from 44-57% of final energy. Material efficiency and demand is highlighted as important for emissions but the overall mitigation potential was not quantified. In four key sub-sectors (cement, steel, chemicals and pulp and paper) that were assessed in greater detail, it was argued that CCS, where CO_2 is captured at tailpipe or as part of the process, compressed and stored permanently underground, is essentially the only option that can reduce CO_2 emissions in the range of 70-90 %. Results along the same lines can be found in the IEA Energy Technology Perspective scenario[18], where most of the 3 $GtCO_2$-eq emission reductions when comparing the 4DS and 2DS low demand scenarios result from energy efficiency and CCS. Fuel and feedstock switching account only for about 10 % (300 $MtCO_2$-eq) of the reduction. A recent roadmap by IRENA for renewable energy in manufacturing up to 2030 emphasized biomass (e.g. biochar in place of coal) as an option for process heat demand[19].

It is increasingly acknowledged that measures beyond energy efficiency technologies are needed if GHG emission reductions in the industry sector are to meet the needed levels[20,21,22,23,24,25]. In a world where a priority is made to maintain a global temperature increase of maximum 1.5-2°C and maximum dematerialization is pursued, production of just iron and steel and cement using BAT would consume 20% of the global GHG budget[26]. Reducing yield losses in materials production, reusing old material, designing for extended product life and light-weight design, and de-materialization are some of the options available, and can be implemented through process innovations and new approaches to design. A recent study from the UK found that a 77% reduction in industry emissions could be achieved by 2050 using known technology[27]. Another study by the German Federal Environment Agency explored more radical technology options for 2050 to show how Germany can reduce GHG-emissions by 95%[28]. For industry, these mitigation options include electrifying all industry to the maximum extent possible, and converting surplus renewable electricity to hydrogen and synthetic methane for fuel and feedstock. A study based on the German state of North-Rhine Westphalia, home to 50% of German energy intensive industry, explores two deep decarbonisation scenarios, one focussing on break-through technologies and electrification and the other on CCUS[29,30,31]. Such options were noted in the IPCC reports, but were not included in the analysis because the IPCC bases its findings on reviews of the existing literature, while the options assumed in the German studies, including the use of electricity/hydrogen and carbon dioxide as a feedstock, are still relatively unknown and unexplored. It is partly the intent of this project to add to this literature in a defensible form acceptable to the IPCC. Finally, it should be noted that every jurisdiction will have its own criteria for acceptable approaches to decarbonization. For Germany, secure gas supplies, biomass sourced or synthetically made, are more than just a climate issue, they are a security issue. Germany also lacks plentiful CO_2 storage potential. In contrast, in North America there is no lack of either secure gas supplies or geological storage for CO_2, and the drivers for an acceptable net-zero gas system would be different.

The foregoing analyses of best available technologies (BAT) and further technology options shows that emissions arising from future growth of industrial output cannot be fully compensated by more efficient technology, partly because very energy-intensive production processes are already near BAT. In order to significantly reduce emissions from energy-intensive sectors, the development and implementation of new breakthrough technologies such as electrification, hydrogen-based processes for steel, alternative cements or CCS become necessary. These technologies, however, may use more energy than conventional BAT, a fact that is most pronounced for CCS. Ambitious low-carbon scenarios for energy-intensive industry therefore would need to rely on a de-carbonised electricity supply.

To complement these findings and put them in a Canadian perspective, we conducted a review of potential decarbonization technologies for Cement, Glass, Iron and Steel, Metal processing, Mining, Refineries, Chemicals, and Pulp & Paper. The results of this review are accumulated and fully referenced in the attached database. Before going into these results in detail we provide two case studies of existing purpose-built deep decarbonization projects.

Case studies of functioning decarbonization projects: The use of CCS by Norway's Statoil to dispose of formation gas CO_2 and H_2S byproducts[32], the Quest upgrader and Alberta Carbon Trunk Line projects[33], and Saskpower's Boundary Dam

One technology that offers the promise of reducing emissions while allowing continued use of fossil fuels is carbon capture and storage (CCS)[34][35]. Various applications for CCS exist, but all share the same premise: a GHG, usually carbon dioxide (CO_2), is captured from fossil fuel combustion or gas processing, and transported to a permanent underground storage site. It may also be potentially used as feedstock for materials or fuels, hence the common addition of "Utilization" to CC(U)S (see the Chemicals section later in this report).

The components of CCS are not new technologies. Separation of CO_2 from raw natural gas is standard industry practice. The CO_2 content of commercial natural gas must be reduced to less than 2.5% before the gas can be transported by pipeline. Raw natural gas is passed through an amine separation process to remove the excess formation CO_2 as well as hydrogen sulphide (H_2S), a poisonous gas. CO_2 is typically vented to the atmosphere, while H_2S is flared or compressed and re-injected into the ground to meet regional air quality regulations.

Starting in 1996, Statoil began pumping formation CO_2 from the Sleipner natural gas platform back underground into a deep saline aquifer along with H_2S[36]. Statoil invested in CCS because of the Norwegian carbon tax of 200 NOK/tonne CO_2e ($33 USD at January 2014 exchange rates) on emissions from the oil and gas sector, which the government increased to 410 NOK ($68 USD) in 2013[37]. Statoil has since carried out a similar process at other facilities. Several projects to capture and inject CO_2 also exist in North America, where its primary purpose is as a solvent and pressurizing agent for enhanced oil recovery, including the Weyburn project in Saskatchewan.

The Alberta government has been active in support of CCS technology, and has provided long term funding for two key projects (two others were cancelled). The first is the Shell Quest Upgrader project which started operation in 2015 and will store 1 Mt of CO_2 from hydrogen production for bitumen upgrading annually. The second is the Alberta Carbon Trunk Line, which will initially move 1.6 Mt/yr from the Northwest Upgrading Redwater Refinery and Agrium fertilizer plants north of Edmonton 240km south to enhanced oil recovery sites in the centre of Alberta. It is designed to eventually transport up to 14.5 Mt/yr.

Most operating CCS projects are based on pre-combustion separation of CO_2 from a gas mixture. CCS can also be used on post-combustion exhaust gases from any large combustion process, opening up the potential application of CCS to a large share of the global economy. Saskpower's Boundary Dam Project, the first commercial scale post-combustion CCS electricity generation project operating in the world, is based on rebuilding a baseload coal-fired generation unit with carbon capture. The project came on line in fall 2014. There have been technical challenges, including difficulties with the CO_2 transfer solution and energy use exceeding design, but Saskpower has continued development given its long run potential. The captured CO_2 is sold and transported by pipeline to nearby oil fields in southern Saskatchewan where it is used for enhanced oil recovery. CO_2 not used for enhanced oil recovery is stored in deep geological storage via the Aquistore Project. In addition to CO_2, SaskPower plans to sell other byproducts captured from the project. Sulphur dioxide (SO_2) will be captured, converted to sulphuric acid and sold for industrial use. Fly ash, another byproduct of coal combustion, will be sold for use in ready-mix concrete, pre-cast structures and concrete products.

While the use of CCS for disposal of NG industry formation gas CO_2 has been an unqualified success, early experiences with post-combustion, amine separation based CCS have been mixed to date. While it is too early to tell, it is possible that the amine separation process used in the NG industry is not sufficient for widespread post combustion applications, and a breakthough in gas separation membranes, enzymatic processing, or a move to oxycombustion or chemical looping (where fossil fuels are combusted/reacted with oxygen and produce CO_2 unmixed with nitrogen) is necessary for CCS to gain widespread acceptance. This highlights the necessity of expanding our potential options through exploration of more electrification or a transition to hydrogen combustion (where water is the only byproduct), all discussed in more depth later.

Before leaving this section, it must be noted that one of the key long term advantages of CCS is that it allows net negative emissions[38], where CO_2 can be taken out of the atmosphere via biomass or air source capture, and then be permanently returned to deep geological formations. Net negative emissions may be necessary for meeting really deep targets, allowing future growth, and reparation of existing damages.

3 RESULTS OF THE TECHNOLOGY REVIEW

The attached database of decarbonization technologies is segregated into cement, glass, iron and steel, metal processing, mining, refineries, chemicals (distinguished by type), pulp and paper, and a generic class applying to most if not all industry sectors. The technologies listed were researched from the academic and trade literatures, and dynamic source links are provided where possible in the database. The database is not meant to be exhaustive but demonstrative of what is technically possible or acceptable for all jurisdictional circumstances, and is meant to be the prototype for a living document that would be maintained and curated at an appropriate institution.

For each sector we have focussed not on technologies that merely improve the performance of existing technologies (e.g. through efficiency), but on those technologies and processes that promise a significant reduction in GHG emissions. This does not mean that efficiency cannot provide significant reductions, but given global demand growth and the needed scale of carbon reductions, energy efficiency alone will not be sufficient.

Where possible the database provides general guidance on the state of technology deployment, expected emission reductions compared to conventional industry technologies and an expression of relative costs. Many of the technologies apply only to new build and so reflect the long-term view towards decarbonisation.

3.1 GENERIC APPROACHES: ELECTRIFICATION, BIOMASS, HYDROGEN, CCUS, & SYNTHETIC HYDROCARBONS

Besides efficiency, the six key generic approaches to reducing GHG emissions in industries that have historically used coal and gas are process electrification, biomass (e.g. biocharcoal from wood in place of coal), hydrogen in place of NG, CCUS, synthetic hydrocarbons (e.g. NG), and finally wholly new processes. Each option has its challenges.

3.1.1 ELECTRIFICATION

Because of its large size and hydropower resource, Canada already has very clean electricity on average, but access to bulk hydroelectricity is regional. The hydropower resource is also finite, for physical and political reasons. To take advantage of its wind and solar resource for industrial use, Canada would need to embark on a substantial renewables building campaign to supply not just traditional electricity customers but to replace much of what is currently supplied by natural gas and coal. Given the intermittency of this resource, it would also need to expand the transmission network while making it stronger and more flexible in terms of timing and volume to electricity transmitted.

3.1.2 BIOMASS SOURCED BIOGAS, BIOLIQUIDS OR BIOCHARCOAL

Biomass is a historically important energy source that was replaced by coal only in the mid-1800s. Because of its carbon neutrality, it has been oft mooted as a replacement for fossil fuels. The sheer volume of fossil fuels that must be replaced compared to the growing land base, and the air quality issues with the combustion of biomass[39], however, preclude it from being more than one component to the solution to climate change. It may, however, provide some key elements to the solution (e.g. biogas from forestry or agricultural waste, switchgrass for liquid cellulosic ethanol as a transport fuel, biodiesel for heavy freight vehicles, biocharcoal as a carbon and energy source in virgin steel making). To the extent bulk biogas could be made from forestry or agricultural waste, it could allow us to continue using the existing NG distribution network, possibly mixed with some hydrogen or synthetic natural gas (see following sections).

3.1.3 HYDROGEN

Hydrogen can potentially be used in place of natural gas, but it must be made and distributed. Hydrogen cannot be transported directly in iron based NG pipes, but it can be used in appropriately chosen plastic pipes. There are two main ways to make hydrogen: steam methane reforming of natural gas (with byproduct CO_2 to dispose of) or electrolysis of water. The two German studies cited earlier directly consider bringing surplus wind energy from the German north to North Rhine Westphalia via low transmission loss high voltage direct current transmission (i.e. like that used to move electricity from Manitoba's dams to load centres), and making hydrogen via electrolysis at the site where it is needed for use in high temperature flame front applications.

3.1.4 CARBON CAPTURE UTILIZATION AND STORAGE (CCUS) & OXYCOMBUSTION

CCUS is a technically viable option for most large combustion industrial facilities, but could be very expensive due to the smaller flue gas volume than electricity generation plants and the need to transport the CO_2 to a disposal site.[40] Northeast BC, Alberta, and Saskatchewan, however, have an enormous storage potential in the deep saline aquifers that underlie most of the Western Canadian Sedimentary Basin (WCSB). Siting of industrial facilities in the WCSB would eliminate most CO_2 transport costs. WCSB geological storage capacity is a clear competitive advantage in a low carbon world.

CCUS becomes more attractive when combined with oxy-combustion, where fuels are combustion in the presence of just oxygen, not air, which is mainly nitrogen. The flue gas is almost pure CO_2, which then does not need flue gas separation. It can be cooled, compressed, stored underground or be used for other processes (e.g. making renewable methanol, see the section on Chemicals). Again, a key long term advantages of CCUS is that it allows net negative emissions, permitting really deep and eventually negative targets if climate sensitivity proves them necessary.

3.1.5 SYNTHETIC HYDROCARBONS (E.G. METHANE, METHANOL AND ETHANOL)

The synthetic renewable NG pathway would allow us to continue using the existing NG distribution network, but synthetic NG requires first making renewable hydrogen from electricity, and then adding sufficient carbon, either from CCUS or air-source capture processes (more on this and especially methanol and ethanol in the Chemicals section). It is a debatable and important question whether it is more expensive to shift our processes to electricity and hydrogen, or to build enough capacity to make synthetic NG and keep our existing end-use technologies.

Beyond methane, there is a growing literature on the possibility of making synthetic renewable fossil fuels (methanol, ammonia, ethylene, propylene), starting with renewable electricity and carbon capture or air sourced CO_2, for both transport and industrial purposes. We address these possibilities in the Chemicals section.

In sum, every country, region and industrial situation may have to consider bespoke solutions based on common building blocks based on the options above. We now consider the sectoral options in detail. Specific technologies identified below indicate in parentheses an estimate of the greenhouse gas emission reduction from conventional technology and/or the current state of development of the technology.

3.2 CEMENT

There are multiple potential technologies for replacing standard Portland cement production with lower and near zero GHG intensity alternatives, including: Novacem (-20% GHG intensity, conceptual), Calera (-99%, conceptual), alkali-activated cement (-95%, pilot), Calix (?, Pilot), Ecocement from incinerator ash (-50%, pilot), thermoplastic carbon-based cements (-50%, pilot), geopolymer cement (-50%, small scale commercial), fuel switching to biomass (variable, commercial), cementitious substitution (-25%, commercial). The last, substitution of cementious materials, is a relatively simple fix where less clinker, the GHG intense portion of cement production, is used for a given portion of cement. It is governed by local construction regulations, and can be made flexible depending on the final application (e.g. whether it is load bearing, etc).

None of the technologies identified can be described as having a particularly Canadian competitive advantage to them, other than that clinker and cement are heavy, have not historically been traded, and are typically produced close to where they are needed. In addition most of the options are not suitable for retrofit, which presents a significant barrier for deployment in the near to mid-term.

3.3 GLASS

Two potential decarbonization technologies were found for glass, oxy-fuel firing (commercial) and direct electric melting (small scale commercial). Depending on the size of facility, the first would ease the use of CCUS because of the high CO_2 content of the flue gas, while the second can potentially have zero emissions, depending on the GHG intensity (and resulting cost) of the electricity.

The direct electric melting technology may have a Canadian competitive advantage associated with our large hydroelectric resource and potential for wind and solar renewables.

3.4 IRON AND STEEL

There are currently three main technologies to make steel: the blast furnace-basic oxygen furnace (BF-BOF) route, direct reduced iron with electric arc furnaces (EAF), and solely via EAFs.[41]

Virgin (i.e. from iron ore) steel is typically made in the blast furnace to basic oxygen furnace (BF-BOF) route, also called “integrated” steel production. This is the most GHG intensive way to make steel and there is limited opportunity to improve GHG intensity beyond current best available technology. Direct reduced iron (DRI) or hot briquetted iron (HBI) can be used in a BF to reduce CO_2 emissions and increase productivity, but historically it has not been economical to do so. It is also important to note that BOFs typically use 20-30% scrap as a feed stock and that the availability of scrap in Ontario (where the three Canadian integrated plants are located) is already being fully utilized with the need to purchase scrap from the US and other countries. Conversion of integrated plants to EAF technology would substantially increase scrap pricing in the short to medium term, and Canada would likely become a net importer of scrap.

EAFs are typically used to melt recycled steel for reuse, and run on electricity. If bulk electricity can be decarbonized, they could make essentially decarbonized steel. Because of the way it is found and gathered, however, the scrap from which recycled steel is made typically has too many impurities (mainly tin, copper, nickel, molybdenum, chromium, and lead) to be used for high performance applications, such as tinplated food cans or automotive “exposed” surfaces (e.g. door skins). Traditional EAF facilities use primarily recycled steel as a feedstock, but some EAFs use combinations of alternative feedstocks including direct DRI, HBI, pig iron, iron granulate, or hot metal from a BF, all of which can lower undesirable residual contaminant levels associated with traditional EAF technology, resulting in higher quality steel.

While EAF steel shops have made attempts to improve scrap sorting, it is not yet economical to remove all sources of undesirable residuals, and tinplate cans require an outlet for recycling. If recycling systems or EAF processors could be set up to sort out these impurities, or products designed so that they are easy to disassemble and processes put in place to do this, the literature indicates recycled steel could be used in up to 50-75% of applications globally by 2050.[42,43,44,45,46] Regional applicability would vary.

A DRI fed EAF results in substantially lower CO_2, but the current technology for producting DRI generates CO_2. The electricity requirements and process time required to melt DRI in an EAF is greater than a scrap fed EAF adding to the cost of production and has implications for GHG emissions if the electricity source is not decarbonized. The cost of DRI is also typically greater than scrap and DRI is generally only used by plants requiring better quality liquid steel or in locations isolated from abundant scrap sources that have access to iron ore and cheap natural gas or coal. The use of hydrogen can potentially lower CO_2 generation during the production of DRI, as being piloted in the Swedish HYBRIT system, but the cost will be directly related to how the hydrogen is produced.

Beyond the standard two technologies, there are limited commercially proven technologies for steel production. Technologies such as Corex and Finex do not reduce CO_2, have higher operating costs and shorter asset life. A number of technologies are in pilot stages that could potentially substantially reduce GHG emissions: HIsarna Smelt Reduction (Coke free steel making) (-20%, pilot); Paired Straight Hearth (PSH) Furnace (-30%, pilot); Coal-Based HYL Process (-60%, pilot) and molten oxide electrolysis (with decarbonized electricity -99%, pilot). The last is most interesting, as it potentially allows for making virgin steel purely with decarbonized electricity. The quantity of electricity required, however, (10 MWh/tonne steel) is twenty to thirty times greater than best in class EAF that currently use 330-500 MWh/tonne steel.

Steel, like cement, tends to be made near the source of raw materials and where there is a market for the product. In the past, Canada made steel using ore from around the Great Lakes and scrap from local manufacturing to make railroad equipment, cars, food cans, building materials and other steel products. Unless it is based on geological storage for CCS or cheap decarbonized electricity, Canada is unlikely to maintain a competitive advantage in bulk steel production. It may, however, if recycled steel can be improved and based on the large existing amount of already processed steel waiting to be recycled at some future date, be able to maintain a more boutique industry serving specialist needs, including vehicles. An important complication is that foreign ownership of integrated steel plants may result in the import of steel slabs, resulting in carbon leakage to other countries and increased carbon footprint due to the transportation of these slabs that would be “finished” in Canada. This would also result in decreased employment and decreased profitability and sustainability of the industry.

3.4 METAL PROCESSING

Much metal processing to date, with some exceptions, has been done by “crushing and melting” of source ores. Both are energy intensive. The crushing may be unavoidable, but it can be done with decarbonized electricity, while the pyrolytic melting (e.g. smelting, roasting) can be replaced with leaching of the desired metal using various tailored solutions (e.g. acids), followed by electrolysis or precipitation of the metal ores from the solution.

Given Canada’s history as a metal producer, and the fact that demand for these metals is unlikely to diminish, Canada has some interest in maintaining its competitive advantage in primary metal extraction and processes by investing in decarbonization technologies for this sector. Not many other countries have such an interest in maintaining the viability of this sector (besides perhaps Australia and Russia), and Canada would be wise to consider some targeted R&D and commercialization aid in this area of its own accord.

3.5 MINING

There are two main avenues for decarbonizing this sector, one specific to coal mining, and one to mining in general.

Coal mines emit a small but significant amount of coal bed methane, a strong GHG. This currently accounts for 15% of all mining GHG emissions. There are two ways to control for coal bed methane: catalytic reaction to CO_2 before it escapes to atmosphere, and capture and combustion of the methane as CO_2, potentially with electricity generation.

More generally, a large portion of mining emissions are from diesel motors used to power ore crushers, ore movement vehicles, make electricity, run pumps and motors, etc. If a sufficient supply of decarbonized electricity is available, ore movement can be largely switched to conveyors belts. Saab-Scania has recently commercialized hybrid diesel-electric freight trucks that can run on high wires, and these could be used for heavy lifting paths at mines (e.g. when ore is moved predictably from one altitude to another, a system of movable high wires can be built). On descent, truck braking could be used to generate electricity. Energy use at a given mine is highly sensitive to its shape (surface stripping vs. deep mine shaft) and depth, and the most effective and efficient methods will be sensitive to these features. If decarbonized electricity is not available in sufficient quantity at remote mine sites, decarbonization of mining will largely depend on decarbonized liquid motor fuels.

3.6 REFINERIES

Refineries take raw and semi processed fossil fuel products (various grades of crude oil and natural gas) and transform them into usable gasoline, diesel, kerosene, and other refined petroleum products. A certain portion of the inherent energy is used in the plant. While the chemistry will be different, their internal function will be largely the same if large scale renewable biofuels (e.g. renewable methanol (see Chemicals), cellulosic ethanol) are produced.

There many ways to make refineries more efficient, especially by capturing and using process heat, but to significantly reduce their emissions some form of carbon capture and storage will be required, via amine processing (current NG sector practise) or eventually via membranes (in the R&D and pilot stage), oxycombustion, or chemical looping. This will require transport and storage of the CO_2.

There are radical technological changes possible for the refinery sector, including the use of air source capture of CO_2 combined with hydrogen made from renewables to make sustainable liquid fossil fuels – see the following section.[47]

3.7 CHEMICALS

While chemicals are treated as a unique sector, processes are different for each product and we have treated them as such. Many technologies were found to make smaller (typically <10%) changes in energy efficiency (see the database); we have focussed on large potential GHG changes.

3.7.1 NET ZERO GHG HYDROGEN – KEYSTONE CHEMICAL

Net zero GHG hydrogen can be made with electrolysis of water, or potentially through photocatalytic processes that already occur in photosynthesis through complex biological reaction pathways. These processes cannot be considered energy efficient, but they are GHG neutral. Electrolysis is a commercial technology, buts its economics are highly dependent on electricity process.

3.7.2 NET ZERO GHG METHANOL – KEYSTONE CHEMICAL

Net zero GHG methanol can be made from any concentrated source of carbon dioxide with the addition of net zero GHG hydrogen. Combustion flue gases are one potential source of CO_2, as is air source capture. This process consists of a system of electrolytic cracking and catalytic synthesis that leads to a low pressure and low temperature electrochemical production of methanol (100% reduction in process GHGs, pilot). This process is similar to air source liquid fuel process described in Refineries. This technology can be considered at the pilot or commercial stage, depending on the CO_2 source.

3.7.3 NET ZERO GHG ETHANOL – LIQUID FUEL

Net zero GHG ethanol can be made from net zero GHG methanol by adding carbon (either air sourced or post combustion sourced) and net zero GHG hydrogen. There are multiple commercial methods with varying costs and associated emission reductions.

3.7.4 OLEFINS (E.G. ETHYLENE, PROPYLENE)

- Catalytic vs steam cracking of naptha to produce olefins (e.g. ethylene), (30-40% reduction in energy use, Pilot)
- Make olefins from natural gas via methanol, replacing the current process of steam cracking of naptha or ethane (10% reduction in energy use, could be combined with net zero GHG methanol)
- Bio-ethylene from bio-ethanol. The bio-ethanol is converted to bio-ethylene by an alumina or silica-alumina catalyst (69% reduction in GHGs, Pilot)

3.7.5 AMMONIA

A simple but currently expensive way to decarbonize ammonia production is to replace natural gas as the hydrogen feedstock with net zero GHG hydrogen made from electrolyzed water (-99% reduction in GHGs, commercial but high cost). Another method is to replace the natural gas feedstock for hydrogen with syngas from biomass (63% reduction in GHGs, commercial)

3.7.6 STYRENE

Carbon dioxide acts as a diluent, shifting and enhancing the equilibrium conversion. The process also improves selectivity and provides improved heat delivery due to high heat capacity (40% reduction in GHGs, Pilot)

3.7.7 GENERIC APPROACHES TO CHEMICAL PRODUCTION

Use of fermentation and enzymatic processes instead of chemical processes with catalytic reactions. Biological processes take place at lower temperature and pressures, reducing energy demand by as much as 50%. An example with the greatest potential worldwide is ethylene produced from bioethanol, instead of petrochemical feedstock. These technologies, while they work at the bulk lab bench scale, should be considered conceptual. Much research is required to ascertain the pros and cons: whether they are scalable, whether reliable feedstocks can be found, process efficiency, time lags between process beginning and end, etc.

Chemical looping combustion - A combustion process with an oxygen carrier circled between two fluidized bed reactors: an air reactor and a fuel reactor. The oxygen carrier is oxidized by introduction of air in the air reactor. Gaseous fuel then reacts with oxygen on the oxygen carrier in the fuel reactor. Carriers are usually a metal (Ni or Fe are common). The process produces a pure water and CO_2 exhaust, which is easier to store geologically or can be used for making methanol and more sophisticated renewable liquid fuels (-95% GHGs, conceptual).

3.8 PULP AND PAPER

The pulp and paper sector is interesting from a decarbonization perspective in that it sits at the nexus of bulk natural CO_2 absorption processes by forests, and thus potential bulk feedstocks for CO_2 absorptive building materials and net-zero transport liquids like cellulosic ethanol. If Kraft pulping processes are involved, the sector also has a surplus of net-zero energy at its disposal from the lignin removed from the wood feedstocks. It is beyond the scope of this project to discuss all the implications of this, but at the very least government and industry representatives should consider the considerable opportunities afforded by the positioning of the sector.

Pulp is made in two main ways, via mechanical or chemical pulping (or a mix). In mechanical pulping machinery tears up the cellulose wood fibre in preparation for paper making, while in chemical pulping the lignin that holds the cellulose together is dissolved. In the latter case the dissolved lignin can be used a biofuel to heat and power the plant using Tomlinson recovery boilers (a net surplus of electricity to the grid is also common). This has become standard practice in new and rebuilt mills with chemical pulping. For mechanical pulping decarbonized electricity is necessary to power the motors.

Canada, and especially Québec and Ontario, has a competitive advantage in pulp and paper production because its has the raw resources and clean electricity, but the industry has been suffering due to reduced demand for newspaper, and it is unclear what will happen to paper demand in the future.

There are multiple avenues to significantly reduce net GHG emissions from the sector, including:

- Conversion of Kraft lime kilns from fossil to renewable fuels
- Production of wood pellets from waste and biomass to allow other sectors to more easily convert to biofuel (e.g. home heating, district energy systems)
- Anaerobic Kraft process effluent treatment to transform effluent into combustible bio-gases and reduce sludge production.
- Novel sludge drying processes to reduce energy use and methane emissions
- Increased use of recycled fibre. While there were initially quality issues, recycled fibre is being increasingly used for higher quality end uses through time.
- Lignin from biomass can be used to produce aromatics.

4 DISCUSSION & CONCLUSIONS

Energy use in Canadian GHG intense industry has not been driven by climate policy up until recently. Competitiveness has driven the move to BAT and high energy prices the move to renewables. As of mid-2016, industry faces a mixture of policy systems from coast to coast, each with compensations for energy intense, trade exposed industry to protect competitiveness (e.g. free permits in Ontario and Québec, carbon tax exemptions for process and fugitives in BC) that send confusing and uncertain long term GHG abatement investment signals. Perhaps the most consistent signal is Alberta's system of penalties for GHG intensity and subsidies for associated output.

While industry has made significant strides in energy efficiency, it must think beyond today's best available technologies to the needs of the latter part of this century if global GHG targets are to be met. The first and most important requirement is a consistent signal to industry to reduce GHG emissions to net-zero within 1-2 capital investment cycles without unduly hurting competitiveness for existing facilities (i.e. inducing sunk costs and stranded assets, and the associated unemployment and social trauma). Industry has the knowhow and experience in deploying capital and successfully implementing major projects. To take advantage of this, policy makers need to create a safe space for industry to bring its expertise to the table by separating the transition phase from the final goal of decarbonization, and managing the transition so as not to strand assets or harm competitiveness.

We have found that technically feasible decarbonization options exist for almost all heavy industry sectors. While there is a deficit of reliable cost data, if one can assume that there will be continuing demand for these commodities in a growing world despite decarbonization, given the focus on decarbonized electricity Canada is likely to retain a cost advantage in a low carbon world. While some of the decarbonization technologies discussed are already commercial given a sufficient supply of reasonably priced decarbonized electricity to use directly or as hydrogen produced using electrolysis, most are at the conceptual and pilot stage, and need intensive R&D and piloting, including carbon capture and storage.

Much R&D support for decarbonization is occurring globally, but it is concentrated in electricity production and personal vehicles. As a result this and the earlier mentioned sheltering of GHG intense, trade exposed industry from climate policy, there is an R&D gap in heavy industry, specifically in primary mineral extraction and processing. If Canada wishes to be competitive in these sectors in the future, it should strongly consider a specifically Canadian heavy industry decarbonization effort built around cooperation between the federal and provincial governments, industry, and research institutions. This requires money to support research, pilot testing and associated labour force training, and above all, consistent climate policy, including carbon pricing, that promises to strengthen through time.

It bears repeating that Canada is one of few developed nations, Australia and Russia being the only other obvious comparators, with a large resource base and the technical know-how to potentially develop it efficiently and effectively in a decarbonized way. Given this, should we give up on heavy industry, let the market decide in a laissez faire fashion, or pursue an active role in maintaining it? Seen from the point of view of an economist, the Canadian economy has three main productive resources: its people, the land, and what capital we've saved and can borrow to provide a living for our population. All these resources have limits and must be used efficiently. The private market must have a role is this decision. However, Canada has been a primary goods producer in one form or another since its modern beginning. Due to our land base we have a very large essential advantage in primary extraction and processing, and the capacity to make and deploy decarbonized electricity in bulk. This would suggest that Canada has a future in decarbonized heavy industry.

If active, should Canada pursue a hard electric path, industry with CCUS, bio/synthetic NG, or a mix? Again as an economist, best practice in environmental regulation is not to dictate how households and firms meet environmental goals, but to clearly define those goals and provide a clear policy framework and incentives to meet them. Canada's emissions must fall approximately 90% in the lifetime of current middle age adults to meet our portion of the global carbon budget. Firms and households, within their set of available options, know best how to do this, and carbon pricing and tradable market orientated regulations (e.g. for car manufacturers) are the best way to motivate their choices.

However, regional resources have much to say in this matter. Alberta, Saskatchewan and to a certain extent BC have much better geological storage opportunities than Ontario and Québec. While all regions should go “hard electric”, CCUS is likely to be more promising strategy in the west than the east. For example, synthetic methane production could make use of CCUS in the west as a source for CO_2, but would need to rely on air source capture in the east. Ontario is perhaps in the most challenging position, as it has much older industry, little geological storage and little new hydropower capacity. In this case its efforts at wind and solar are really its main path forward short of nuclear power, and it has the most to gain from research and experimentation with advanced alternative processes. Ontario and Québec may usefully think of themselves as a potential “test-labs” for non-CCUS orientated heavy industry research, and piloting and demonstration sites for low carbon heavy industrial technologies.

What policies are required? First and foremost, Canada and its regions need a heavy industry decarbonization R&D effort focussed on its particular competitive advantages (electrification, primary extraction and processing, reorganization of steel recycling to make high value products, biomass for bio-chemical products and fuels). Second, heavy industry needs to work with the federal government to ensure both policy certainty and a level trading ground with our trading partners. We should push climate policy as fast as we can, but be firm with our trading partners that the same stringency will apply to them (through WTO compliant border tax adjustments, etc.). Third, we need short, medium and long run planning and decision making to mange the transition, and put in place and maintain the right infrastructure. While an expanded, thickened and smarter electricity network is obvious, there are other important elements. Do we need to preserve the natural gas network for bio/synthetic natural gas, or to let it decay and move strongly to pure electrification? In an environment of strong uncertainty and learning, the preservation of the natural gas network option deserves strong consideration.

In the same vein as the NG network, serious consideration must also be given to the capital base in other high capital and long-term investment sectors like Cement, Glass, Iron and Steel, Metal Processing, Mining, Refineries, Chemicals, and Pulp & Paper. To keep Canada open for business in these sectors we will have to be completely re-invent these sectors from where we are now, as Alberta is trying to do with the oil and gas sector and its Climate Leadership Plan. We need a coherent plan to attract new low-carbon capital investment, and have a fair exit plan for facilities and associated communities where little can be done. For example, as the global newsprint industry suffers, existing pulp and paper facilities and their associated communities have been feeling the effects. Some of the locations may be ideally located for biofuel production, and serious consideration should be given to what it would take to accomplish this in terms of planning, infrastructure, investment and retraining.

In conclusion, Canada has a potentially very bright future in decarbonized heavy industry, but the private market will not accomplish this completely of its own accord; planning, R&D, infrastructure investment and retraining are required by industry and all levels of government.

4.1 EPILOGUE

The initial idea for the attached database was that it could evolve into an living document, a public open source resource for energy modellers and other interested parties. While this idea is at odds with the naturally competitive and secretive nature of industrial technology, its purpose is to show at least where the boundaries of the envelope are, and that decarbonization is possible. I have approached several other modellers and modelling teams and several are interested in adding to the database (e.g. University College London and Lund University). I am also looking for a host institution for the database, Canadian or otherwise, and will continue to pursue expansion and ongoing curation of the database.

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Industry	Technology or process type	Technology or process name	Description	State of development	GHG impact	Energy impact	Cost	Policy	Considerations for application in Canada	Reference type
				Current standard, commercial, pilot, R&D, conceptual?	Quantify in relative to current standard	Does the technology require greater or lesser energy consumption? Different fuel?	Capital, \$/t CO_2, other	Have any jurisdictions implemented policies (e.g. R&D) to pursue this technology?		References should be peer-reviewed or from otherwise reputable sources.
Cement										
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				
Cement	New decarbonization technology/process	Novacem	Cement composed of magnesium oxide and hydrated magnesium carbonates. Produced at lower temperature (180C vs 1250C) and pressure to reduce combustion emissions, as well as allow for biofuel substitution. Absorbs more CO_2 than is produced during the process, leading to an absorption of ~100kg CO_2 per tonne cement produced. Product is air permeable.	Conceptual	Absorbs 100kg CO_2/t clinker	30% less than OPC	Magnesium is not very common on land, making this option more expensive			Survey academic article covering novel methods of cement production.
Cement	New decarbonization technology/process	Calera	Cement production that mimics coral reefs. CO_2-rich flue gas is filtered through seawater. Calcium and magnesium are stripped from seawater to create cement as strong as OPC, and air permeable (potential building efficiency benefits). Similar product to Novacem but different process.	Conceptual	Essentially would be carbon neutral, as carbon comes from recycled effluent	Less				Survey academic article covering novel methods of cement production.
Cement	New decarbonization technology/process	Alkali-Activated Cement	Aluminum-silicon based cement, made from sand, water, natural or synthetic pozzolands and an alkali activator. Competitive in terms of cost with OPC as well as strength.	Pilot	95% less emissions than standard OPC	Less				Survey academic article covering novel methods of cement production.
Cement	New decarbonization technology/process	Calix	Produced in a reactor by rapid calcination of dolomitic rock in superheated steam.	Pilot				New Build Only	Acceptance and confidence in durability	Technology Roadmap
Cement	New decarbonization technology/process	Ecocement from incinerator ash	500 kg/ton clinker replaced by incinerator ash	Pilot	50% CO_2 reduction			New Build Only		Technology Roadmap
Cement	New decarbonization technology/process	Thermoplastic carbon-based cements (C-Fix cement)	Produced as a waste/residue when crude oil is ´cracked´. C-Fix was developed by Shell and the University of Delft (NL) and needs to be heated to 200°C before being added to aggregates/fillers to make a ´carbon concrete´. It has properties in common with both asphalt and cement-based concretes but is mixed and applied using asphalt techniques.	Pilot	50% CO_2 reduction			New Build Only	Acceptance and confidence in durability	Technology Roadmap
Cement	New decarbonization technology/process	Geopolymer Cement	Utilises waste materials from the power industry (fly ash, bottom ash), the steel industry (slag), and from concrete waste, to make alkali-activated cements.	Small Scale Commercialization	50% CO_2 reduction			New Build Only	Acceptance and confidence in durability	Technology Roadmap

Industry	Technology or process type	Technology or process name	Description	State of development	GHG impact	Energy impact	Cost	Policy	Considerations for application in Canada	Reference type
				Current standard, commercial, pilot, R&D, conceptual?	Quantify in relative to current standard	Does the technology require greater or lesser energy consumption? Different fuel?	Capital, $/t CO_2, other	Have any jurisdictions implemented policies (e.g. R&D) to pursue this technology?		References should be peer-reviewed or from otherwise reputable sources.
Cement	Cementitious substitution	Cementitious substitution	Increase use of clinker substitutes	Commercial	260 kgCO2/tonne of cement produced (based on move from 0.88 to 0.6 tonne clinker per tonne cement)		€-25 to -30/tCO2		Availabilty of supply of substitute materials and sutability for different applications	Technology Roadmap
Cement	Fuel switching to biomass	Fuel switching to biomass	Increase of biomass	Commercial	31% CO2 reduction		Capital: €5-15 million for retrofit. Operational: €2-8/tonne clinker increase		Availabilty of supply and price of biomass fuels	Technology Roadmap
Glass										
Glass	New decarbonization technology/process	Oxy-fuel firing		Commercial		Between 5-20% of fuel savings compared to efficient regenerative furnaces, At least 15% more efficient than conventional air fired burner systems.	Heavily dependent on the size of the furnace			Technology Roadmap
Glass	New decarbonization technology/process	Direct Electric Melting	Electric furnace	Small Scale Commercialization	Eliminate fossil fuel combustion emissions	Relatively more efficient	Driven by cost of electricity	New Build Only		Technology Roadmap
Iron and Steel										
Iron and Steel	Current Technology	BF-BOF	Blast furnace + basic oxygen furnace technology for the majority of production, Electric Arc Furnace EAF also used for recycling steel.	Current Standard	Global average: 2.1 tCO2/tonne steel BF-BOF +0.2 casting and rolling;	10 GJ/t				Literature review

Industry	Technology or process type	Technology or process name	Description	State of development	GHG impact	Energy impact	Cost	Policy	Considerations for application in Canada	Reference type
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	Current Technology	EAF	Electric Arc Furnace	Current Standard	EAF depends on electric GHG intensity plus +0.2 casting and rolling.					Literature review
	Current Technology	DRI-EAF	The DRI process uses natural gas (90% globally) or coal (10%, mainly in India) for energy and a syngas of hydrogen and carbon monoxide as the reductant. After reduction, the metallic iron is then melted in an EAF	Current Standard	1.4 tCO_2/tonne + EAF needs + 0.2 casting and rolling				EAF are irutaully GHG free in hydroprovinces: Quebec, Manitoba and BC.	Literature review
Iron and Steel	New decarbonization technology/process	Cyclone Converter Furnace	Pre-reduction and final reduction of iron ore takes place at different levels within the same cyclone, reducing heat losses of different steps. Oxygen and coal (or other biomass) is introduce at the bottom of the cyclone.	R&D	Less	20% reduction				Survey peer-reviewed article covering novel methods of Iron and Steel production.
Iron and Steel	New decarbonization technology/process	Smelt Reduction (Coke free steel making)	HIsarna technology uses a bath-smelting technology and produces a more energy efficient and less carbon intensive steel. It combines a number of processes, preheating of coal, partial pyrolysis in a reactor, an ore melting cyclone and a vessel for ore reduction.	Pilot	20% CO_2 emission reductions		Estimates are that both capital and operating expenditures would be lower.		Requires replacement of entire blast furnace	Technology Roadmap
Iron and Steel	New decarbonization technology/process	Paired Straight Hearth (PSH) Furnace	Pellets of Iron and high-volatility Coal are heated and reduced to 95% metallized pellets suitable for use in an EAF. The product of reduction (CO gas) is released and heated above the bed to drive the process. More efficient than traditional Blast Furnace.	Pilot	33% reduction per t of hot metal produced	30% reduction compared to blast furnace	\$16.7 M for facility producing 46,000 t a year of DRI			Survey peer-reviewed article covering novel methods of Iron and Steel production.

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Iron and Steel	New decarbonization technology/process	Coal-Based HYL Process	Gasified coal is used to directly reduce iron ores in a solid-gas moving bed reactor.Oxygen is removed from ores using reactions based on H2 and CO to create highly metallized DRI. Can gasify and use pretty much any carbon-bearing fuel.	Pilot	60% reduction	Less				Survey peer-reviewed article covering novel methods of Iron and Steel production.
Iron and Steel	Increased used of recycled steel	Increased used of recycled steel	Most virgin steel is made using the BF-BOF process, while recycled steel is almost entirely produced using an electric arc furnace. The lower the GHG intensity of electricity, the lower the process GHG intensity. According to J. Allwood, in most developed coutnires there is sufficent recyclable steel available to meet all needs, but it tends to be contaminated with tin and copper. If these could be seperated, either through design or labour, the mix of recycled steel in the overall mix could rise.	Conceptual, would require industrial reorgnisation	up to -99%, -50-75% given recyling estimates	Less			Highly applicable to Canada, given our existing vehicle and building stock.	Survey. Document not pee reviewed but based on peer reviewed literature.
Iron and Steel, Chemicals	New decarbonization technology/process	MOE	Molten oxide electrolysis for steel production with iron-chromium alloy anode. Electricity will drive the process instead of fossil fuel combustion, with carbon added to form steel simply as needed.	R&D	80% reduction compared to blast furnace per t of liquid steel	Uncertain				Survey peer-reviewed article covering novel methods of Iron and Steel production.
Metal Processing										
Mining, Metal Processing, Chemicals	New decarbonization technology/process	Solar Thermal Process Heat	Solar thermal steam heating can be applied to manufacturing processes requiring temperatures up to 400C. For example, there is a 50 GWh solar thermal installation at a copper mine in Chile.	Pilot		Uncertain				Industry association publication
Metal processing	New/repurposed decarbonization technology/process	Switching from pyrolytic to hydrolytic processes		R&D	Case specific.					

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Mining										
Mining	Current Technology	Release of VAM	Currently Methane emissions leaking from coal mines are released into the atmosphere, at high flow rates but low methane volumes (0.2% - 1.0%) accounting for ~15% of mining emissions.	Current Standard						
Mining	New decarbonization technology/process	Stone Dust Looping Process	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.	Conceptual	Depends on starting mine site emissions	Uncertain				Peer-reviewed article
Mining	New decarbonization technology/process	VamTurBurner	Technology for reducing VAM from coal mines. Essentially a turbine which combusts methane, using heat exchangers to produce electricity as well as heat incoming gas. Can lead to higher efficiency burning as well as turning a source of emissions into useful product.	Conceptual	Depends on starting mine site emissions	Less				Peer-reviewed article
Mining	New decarbonization technology/process	Switching mine trucks to hybrid diesel/electric motors, that can be driven using overhead wiring		Technology well known, has not been applied in this sector	Depends on access to electricity at remoate mine site, plus GHG content of electricity. Material available, need to fill out		If new build and electricity available, could be net negligible because of the cost fop transporting in diesel.		Some mine sites are close to decarbonized electricity (e.g. .in the Yukon and NWT), some are not.	Consulting review report
Mining	New decarbonization technology/process	Use of electric conveyor belts to move ore instead of diesel trucks		Commercial	Depends on access to electricity at remoate mine site, plus GHG content of electricity. Material available, need to fill out		If new build and electricity available, could be net negligible because of the cost fop transporting in diesel.		Some mine sites are close to decarbonized electricity (e.g. .in the Yukon and NWT), some are not.	Consulting review report

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Refineries										
Refineries	Current Technology	Current Technology	Currently refineries do not employ any method of capturing CO2 emissions, either by filtration, adsorption or scrubbing.	Current Standard	0.35 t CO2/ m3 output					
Refineries	Energy Efficiency	Waste Heat and Energy Recovery	High efficiency energy recovery units for exporting heat to local industrial or domestic users or electricity to grid (fluid catalytic cracking units, hydrocracking units, coking units)	Commercial	10% Reduction		Project Investment is more than 5 million pounds		Requires a demand for waste heat	Technology Roadmap
Refineries	New decarbonization technology/process	Air source capture combined with hydrogen sourced from renewable electricity to make liquid fuels		Pilot	Depending on how done, could be -99%					Website with peer reviewed sources
Refineries	New decarbonization technology/process	Post-Combustion Membranes	Membrane technology used to adsorb or separate CO2 from flue gas. Captured CO2 would be condensed. Low maintenance.	R&D	Up to 95% reduction	None	$48/t (75% removal) - $71/t (90% removal)			Peer-reviewed article
Chemicals										
Chemicals	Current Technology	Current Technology	Chemical manufacturing in Ontario/QC has GHG per output of around 0.80 tCo2/t output. Most processes used chemical catalysts, which require higher temperature and energy input than biological processes.	Current Standard	~0.80 t CO2 / t output					
Chemicals - Methanol	New decarbonization technology/process	Carbon Dioxide to Renewable Methanol	Methanol produced from flue gases that contain a high concentration of carbon dioxide and hydrogen. This process consists of a system of electrolytic cracking and catalytic synthesis that leads to a low pressure and low temperature electrochemical production of methanol.	Pilot	100% Reduction (potential for net sequestration 1.13 tCO2e/t of methanol)		USD$8.4 million for 50 million litre facility	New Build Only	Technology must be deployed near an industrial site that can produce high CO2 waste streams.	Non peer-reviewed article
Chemicals - Olefins	New decarbonization technology/process	Olefins: Catalytic Cracking of Naphtha	Olefins (ethylene, propylene, etc.) usually produced by steam cracking, which is energy intensive. These can be created by catalytically cracking Naphtha instead, which requires less energy.	Pilot		30 - 40% less				Peer-reviewed article
Chemicals - Olefins	New decarbonization technology/process	Olefins: Methane to Olefins	Make olefins from natural gas via methanol, replacing the current process of steam cracking of naptha or ethane	Pilot	10% reduction	reduces fossil fuel by about 66%		New Build Only		Technology Roadmap

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Chemicals - Ethylene	New decarbonization technology/process	Olefins: Bio-ethylene	Bio-ethylene from bio-ethanol. The bio-ethanol is converted to bio-ethylene by an alumina or silica-alumina catalyst.	Small scale commercialization	69% Reduction, 0.057 tCO2e/t product (vs. natural gas)		16 Euros/tCO2e	New Build Only		Technology Roadmap
Chemicals - Ethylene	New decarbonization technology/process	Catalytic Coating of Coils	Reducing coking can greatly improve heat transfer in furnaces. A novel catalytic coating is applied to the internal surfaces of tubes and coils that can greatly reduce coke formation and also allow higher ethylene selectivity.	Pilot	6% reduction	6-10% reduction				Non peer-reviewed article
Chemicals - Aromatics	New decarbonization technology/process	Lignin to Aromatics	Lignin (mainly from woody biomass) can be used as a feedstock for producing aromatics. Lignin must be first depolymerized and defuncionalized. Energy impact is probably greater, but GHG's associated with life cycle will be lower.	Conceptual	Less	More				Non peer-reviewed article
Chemicals	Current Technology	Steam Reforming Hydrogen Production	Steam and methane combine to create syngas; oxygen is then strippe dfrom water to oxidize CO to CO_2.	Current Standard	9 - 12 t CO_2 / t Hydrogen					
Chemicals - Hydrogen	New decarbonization technology/process	Photocatalytic Hydrogen Production	Creation of hydrogen from water through photocatalytic processes that already occur in photosynthesis through complex biological reaction pathways. Lots of energy input required, but does not require fossil fuels.	Conceptual	Less	More				Non peer-reviewed article
Chemicals - Ammonia	New decarbonization technology/process	Solid State Synthesis	Solid state ammonia synthesis using electricity	Pilot				New Build Only		Technology Roadmap
Chemicals - Ammonia	New decarbonization technology/process	Low pressure catalyst for ammonia synthesis	Synthesis of ammonia takes place on an iron catalyst at lower pressure and temperature. Catalysts utilizing ruthenium allow even lower pressure	Early Commercialization	7% Reduction					
Chemicals - Ammonia	New decarbonization technology/process	Biomass gasification to produce syngas	Replacing natural gas feedstock with syngas from biomass for low carbon source of hydrogen for the production of ammonia	Commercial	63% Reduction		300-400 Euros / Mtonne NH_3 produced, ~31 Euros/tonne	New Build Only	Sourcing of biomass	Technology Roadmap
Chemicals - Chlorine	New decarbonization technology/process	Retrofit ODC for chlorine production	Retrofit Oxygen Depolarised Cathode (ODC) to membrane cells	Small Scale Commercialization	23% reduction	23% reduction				Technology Roadmap

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Chemicals - Styrene	New decarbonization technology/process	Dehydrogenation in carbon dioxide	Carbon dioxide acts as a diluent, shifting and enhancing the equilibrium conversion. The process also improves selectivity and provides improved heat delivery due to high heat capacity.	Pilot	40% Reduction	2.5 GJ/t-styrene, compared to 6.3 GJ/tonne styrene for the current process	Retrofit $US10-15 million (250,000 t/yr plant)			Non peer-reviewed article
Chemicals - Generic	New decarbonization technology/process	Membrane Technology	Deploy membrane technologies to replace more energy intensive separation technologies such as distillation	Pilot	8% reduction	8% reduction				Technology Roadmap
Chemicals - Generic	New decarbonization technology/process	Use of enzymatic versus chemical catalytic process	Use of fermentation and enzymatic processes instead of chemical processes with catalytic reactions. Biological processes take place at lower temperature and pressures, reducing energy demand by as much as 50%. An example with the greatest potential worldwide is ethylene produced from bioethanol, instead of petrochemical feedstock.	Conceptual		Up to 50% less	$1-5 /tonne of CO2 saved			Peer-reviewed article

Industry	Technology or process type	Technology or process name	Description	State of development	GHG impact	Energy impact	Cost	Policy	Considerations for application in Canada	Reference type
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Pulp and Paper										
Pulp and Paper	Biomass and clean electricity	NA	The majority of emissions are associated with heat and steam production, as well as electricity. According to the EPA (see reference), increasing biomass and clean electricity compared to natural gas is the best feasible abatement option.	Commercial						Non peer-reviewed article
All sectors										
Metal Processing, Iron and Steel, Chemicals, Cement and Glass	New decarbonization technology/process	Chemical Looping Combustion	A combustion process with an oxygen carrier circled between two fluidized bed reactors: an Air Reactor and a Fuel Reactor. Oxygen carrier is oxidized by introduction of air in AR. Gaseous fuel then reacts with oxygen on oxygen carrier in the FR. Carriers are usually a metal (Ni or Fe are common).	Conceptual	95% CO_2 capture	Uncertain				Peer-reviewed article

Industry	Technology or process type	Technology or process name	Description	State of development	GHG impact	Energy impact	Cost	Policy	Considerations for application in Canada	Reference type	Reference links
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Cement											
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					CIEEDAC
Cement	New decarbonization technology/process	Novacem	Cement composed of magnesium oxide and hydrated magnesium carbonates. Produced at lower temperature (180C vs 1250C) and pressure to reduce combustion emissions, as well as allow for biofuel substitution. Absorbs more CO_2 than is produced during the process, leading to an absorption of ~100kg CO_2 per tonne cement produced. Product is air permeable.	Conceptual	Absorbs 100kg CO_2/t clinker	30% less than OPC	Magnesium is not very common on land, making this option more expensive			Survey academic article covering novel methods of cement production.	http://www.sciencedirect.com/science/article/pii/S2212609013000071
Cement	New decarbonization technology/process	Calera	Cement production that mimics coral reefs. CO_2-rich flue gas is filtered through seawater. Calcium and magnesium are stripped from seawater to create cement as strong as OPC, and air permeable (potential building efficiency benefits). Similar product to Novacem but different process.	Conceptual	Essentially would be carbon neutral, as carbon comes from recycled effluent	Less				Survey academic article covering novel methods of cement production.	http://www.sciencedirect.com/science/article/pii/S2212609013000071
Cement	New decarbonization technology/process	Alkali-Activated Cement	Aluminum-silicon based cement, made from sand, water, natural or synthetic pozzolands and an alkali activator. Competitive in terms of cost with OPC as well as strength.	Pilot	95% less emissions than standard OPC	Less				Survey academic article covering novel methods of cement production.	http://www.sciencedirect.com/science/article/pii/S2212609013000071
Cement	New decarbonization technology/process	Calix	Produced in a reactor by rapid calcination of dolomitic rock in superheated steam.	Pilot				New Build Only	Acceptance and confidence in durability	Technology Roadmap	https://www.iea.org/publications/freepublications/publication/Cement.pdf
Cement	New decarbonization technology/process	Ecocement from incinerator ash	500 kg/ton clinker replaced by incinerator ash	Pilot	50% CO_2 reduction			New Build Only		Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Cement	New decarbonization technology/process	Thermoplastic carbon-based cements (C-Fix cement)	Produced as a waste/residue when crude oil is ´cracked´. C-Fix was developed by Shell and the University of Delft (NL) and needs to be heated to 200°C before being added to aggregates/fillers to make a ´carbon concrete´. It has properties in common with both asphalt and cement-based concretes but is mixed and applied using asphalt techniques.	Pilot	50% CO_2 reduction			New Build Only	Acceptance and confidence in durability	Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Cement	New decarbonization technology/process	Geopolymer Cement	Utilises waste materials from the power industry (fly ash, bottom ash), the steel industry (slag), and from concrete waste, to make alkali-activated cements.	Small Scale Commercialization	50% CO_2 reduction			New Build Only	Acceptance and confidence in durability	Technology Roadmap	https://www.iea.org/publications/freepublications/publication/Cement.pdf

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Cement	Cementitious substitution	Cementitious substitution	Increase use of clinker substitutes	Commercial	260 kgCO2/tonne of cement produced (based on move from 0.88 to 0.6 tonne clinker per tonne cement)		€-25 to -30/tCO2		Availabilty of supply of substitute materials and sutability for different applications	Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Cement	Fuel switching to biomass	Fuel switching to biomass	Increase of biomass	Commercial	31% CO2 reduction		Capital: €5-15 million for retrofit. Operational: €2-8/tonne clinker increase		Availabilty of supply and price of biomass fuels	Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050
Glass											
Glass	New decarbonization technology/process	Oxy-fuel firing		Commercial		Between 5-20% of fuel savings compared to efficient regenerative furnaces, At least 15% more efficient than conventional air fired burner systems.	Heavily dependent on the size of the furnace			Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Glass	New decarbonization technology/process	Direct Electric Melting	Electric furnace	Small Scale Commercialization	Eliminate fossil fuel combustion emissions	Relatively more efficient	Driven by cost of electricity	New Build Only		Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Iron and Steel											
Iron and Steel	Current Technology	BF-BOF	Blast furnace + basic oxygen furnace technology for the majority of production, Electric Arc Furnace EAF also used for recycling steel.	Current Standard	Global average: 2.1 tCO2/tonne steel BF-BOF +0.2 casting and rolling;	10 GJ/t				Literature review	Denis-Ryan, A., C. Bataille & F. Jotzo (2016): Managing carbon-intensive materials in a decarbonizing world without a global price on carbon, Climate Policy, DOI: 10.1080/14693062.2016.1176008. Supplemental material

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	Current Technology	EAF	Electric Arc Furnace	Current Standard	EAF depends on electric GHG intensity plus +0.2 casting and rolling.					Literature review	Denis-Ryan, A., C. Bataille & F. Jotzo (2016): Managing carbon-intensive materials in a decarbonizing world without a global price on carbon, Climate Policy, DOI: 10.1080/14693062.2016.1176008. Supplemental material
	Current Technology	DRI-EAF	The DRI process uses natural gas (90% globally) or coal (10%, mainly in India) for energy and a syngas of hydrogen and carbon monoxide as the reductant. After reduction, the metallic iron is then melted in an EAF	Current Standard	1.4 tCO_2/tonne + EAF needs + 0.2 casting and rolling				EAF are irutaully GHG free in hydroprovinces: Quebec, Manitoba and BC.	Literature review	Denis-Ryan, A., C. Bataille & F. Jotzo (2016): Managing carbon-intensive materials in a decarbonizing world without a global price on carbon, Climate Policy, DOI: 10.1080/14693062.2016.1176008. Supplemental material
Iron and Steel	New decarbonization technology/process	Cyclone Converter Furnace	Pre-reduction and final reduction of iron ore takes place at different levels within the same cyclone, reducing heat losses of different steps. Oxygen and coal (or other biomass) is introduce at the bottom of the cyclone.	R&D	Less	20% reduction				Survey peer-reviewed article covering novel methods of Iron and Steel production.	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S136403211400152X
Iron and Steel	New decarbonization technology/process	Smelt Reduction (Coke free steel making)	HIsarna technology uses a bath-smelting technology and produces a more energy efficient and less carbon intensive steel. It combines a number of processes, preheating of coal, partial pyrolysis in a reactor, an ore melting cyclone and a vessel for ore reduction.	Pilot	20% CO_2 emission reductions		Estimates are that both capital and operating expenditures would be lower.		Requires replacement of entire blast furnace	Technology Roadmap	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/230949/D13_951813__Ricardo_AEA_Industrial_Decarbonisation_Literature_Review_201___.pdf
Iron and Steel	New decarbonization technology/process	Paired Straight Hearth (PSH) Furnace	Pellets of Iron and high-volatility Coal are heated and reduced to 95% metallized pellets suitable for use in an EAF. The product of reduction (CO gas) is released and heated above the bed to drive the process. More efficient than traditional Blast Furnace.	Pilot	33% reduction per t of hot metal produced	30% reduction compared to blast furnace	$16.7 M for facility producing 46,000 t a year of DRI			Survey peer-reviewed article covering novel methods of Iron and Steel production.	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S136403211400152X

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Iron and Steel	New decarbonization technology/process	Coal-Based HYL Process	Gasified coal is used to directly reduce iron ores in a solid-gas moving bed reactor.Oxygen is removed from ores using reactions based on H2 and CO to create highly metallized DRI. Can gasify and use pretty much any carbon-bearing fuel.	Pilot	60% reduction	Less				Survey peer-reviewed article covering novel methods of Iron and Steel production.	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S136403211400152X
Iron and Steel	Increased used of recycled steel	Increased used of recycled steel	Most virgin steel is made using the BF-BOF process, while recycled steel is almost entirely produced using an electric arc furnace. The lower the GHG intensity of electricity, the lower the process GHG intensity. According to J. Allwood, in most developed coutnires there is sufficent recyclable steel available to meet all needs, but it tends to be contaminated with tin and copper. If these could be seperated, either through design or labour, the mix of recycled steel in the overall mix could rise.	Conceptual, would require industrial reorgnisation	up to -99%, -50-75% given recyling estimates	Less			Highly applicable to Canada, given our existing vehicle and building stock.	Survey. Document not pee reviewed but based on peer reviewed literature.	https://www.cam.ac.uk/system/files/a_bright_future_for_uk_steel_2.pdf
Iron and Steel, Chemicals	New decarbonization technology/process	MOE	Molten oxide electrolysis for steel production with iron-chromium alloy anode. Electricity will drive the process instead of fossil fuel combustion, with carbon added to form steel simply as needed.	R&D	80% reduction compared to blast furnace per t of liquid steel	Uncertain				Survey peer-reviewed article covering novel methods of Iron and Steel production.	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S136403211400152X
Metal Processing											
Mining, Metal Processing, Chemicals	New decarbonization technology/process	Solar Thermal Process Heat	Solar thermal steam heating can be applied to manufacturing processes requiring temperatures up to 400C. For example, there is a 50 GWh solar thermal installation at a copper mine in Chile.	Pilot		Uncertain				Industry association publication	http://irena.org/remap/REmap%202030%20Renewable-Energy-in-Manufacturing.pdf
Metal processing	New/repurposed decarbonization technology/process	Switiching from pyrolytic to hydrolytic processes		R&D	Case specific.						

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				Current standard, commercial, pilot, R&D, conceptual?	Quantify in relative to current standard	Does the technology require greater or lesser energy consumption? Different fuel?	Capital, \$/t CO_2, other	Have any jurisdictions implemented policies (e.g. R&D) to pursue this technology?		References should be peer-reviewed or from otherwise reputable sources.	Live link
Mining											
Mining	Current Technology	Release of VAM	Currently Methane emissions leaking from coal mines are released into the atmosphere, at high flow rates but low methane volumes (0.2% - 1.0%) accounting for ~15% of mining emissions.	Current Standard							
Mining	New decarbonization technology/process	Stone Dust Looping Process	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 CO2 and then capturing CO2.	Conceptual	Depends on starting mine site emissions	Uncertain				Peer-reviewed article	http://www.sciencedirect.com/science/article/pii/S0378382015301089
Mining	New decarbonization technology/process	VamTurBurner	Technology for reducing VAM from coal mines. Essentially a turbine which combusts methane, using heat exchangers to produce electricity as well as heat incoming gas. Can lead to higher efficiency burning as well as turning a source of emissions into useful product.	Conceptual	Depends on starting mine site emissions	Less				Peer-reviewed article	http://www.sciencedirect.com/science/article/pii/S135943111500455X
Mining	New decarbonization technology/process	Switching mine trucks to hybrid diesel/electric motors, that can be driven using overhead wiring		Technology well known, has not been applied in this sector	Depends on access to electricity at remoate mine site, plus GHG content of electricity. Material available, need to fill out		If new build and electricity available, could be net negligible because of the cost fop transporting in diesel.		Some mine sites are close to decarbonized electricity (e.g. .in the Yukon and NWT), some are not.	Consulting review report	Provide link to BC hydro MKJA report on electrification. TBD.
Mining	New decarbonization technology/process	Use of electric conveyor belts to move ore instead of diesel trucks		Commercial	Depends on access to electricity at remoate mine site, plus GHG content of electricity. Material available, need to fill out		If new build and electricity available, could be net negligible because of the cost fop transporting in diesel.		Some mine sites are close to decarbonized electricity (e.g. .in the Yukon and NWT), some are not.	Consulting review report	Provide link to BC hydro MKJA report on electrification. TBD.

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Refineries											
Refineries	Current Technology	Current Technology	Currently refineries do not employ any method of capturing CO2 emissions, either by filtration, adsorption or scrubbing.	Current Standard	0.35 t CO2/ m3 output						
Refineries	Energy Efficiency	Waste Heat and Energy Recovery	High efficiency energy recovery units for exporting heat to local industrial or domestic users or electricity to grid (fluid catalytic cracking units, hydrocracking units, coking units)	Commercial	10% Reduction		Project Investment is more than 5 million pounds		Requires a demand for waste heat	Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050
Refineries	New decarbonization technology/process	Air source capture combined with hydrogen sourced from renewable electricity to make liquid fuels		Pilot	Depending on how done, could be -99%					Website with peer reviewed sources	http://carbonengineering.com/publications/
Refineries	New decarbonization technology/process	Post-Combustion Membranes	Membrane technology used to adsorb or separate CO2 from flue gas. Captured CO2 would be condensed. Low maintenance.	R&D	Up to 95% reduction	None	$48/t (75% removal) - $71/t (90% removal)			Peer-reviewed article	https://www.researchgate.net/publication/271588841_Membrane-based_carbon_capture_from_flue_gas_A_review
Chemicals											
Chemicals	Current Technology	Current Technology	Chemical manufacturing in Ontario/QC has GHG per output of around 0.80 tCo2/t output. Most processes used chemical catalysts, which require higher temperature and energy input than biological processes.	Current Standard	~0.80 t CO2 / t output						
Chemicals - Methanol	New decarbonization technology/process	Carbon Dioxide to Renewable Methanol	Methanol produced from flue gases that contain a high concentration of carbon dioxide and hydrogen. This process consists of a system of electrolytic cracking and catalytic synthesis that leads to a low pressure and low temperature electrochemical production of methanol.	Pilot	100% Reduction (potential for net sequestration 1.13 tCO2e/t of methanol)		USD$8.4 million for 50 million litre facility	New Build Only	Technology must be deployed near an industrial site that can produce high CO2 waste streams.	Non peer-reviewed article	http://www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland/
Chemicals - Olefins	New decarbonization technology/process	Olefins: Catalytic Cracking of Naphtha	Olefins (ethylene, propylene, etc.) usually produced by steam cracking, which is energy intensive. These can be created by catalytically cracking Naphtha instead, which requires less energy.	Pilot		30 - 40% less				Peer-reviewed article	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S0016236116000612
Chemicals - Olefins	New decarbonization technology/process	Olefins: Methane to Olefins	Make olefins from natural gas via methanol, replacing the current process of steam cracking of naptha or ethane	Pilot	10% reduction	reduces fossil fuel by about 66%		New Build Only		Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

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Chemicals - Ethylene	New decarbonization technology/process	Olefins: Bio-ethylene	Bio-ethylene from bio-ethanol. The bio-ethanol is converted to bio-ethylene by an alumina or silica-alumina catalyst.	Small scale commercialization	69% Reduction, 0.057 tCO2e/t product (vs. natural gas)		16 Euros/tCO2e	New Build Only		Technology Roadmap	http://www.cedelft.eu/publicatie/identifying_breakthrough_technologies_for_the_production_of_basic_chemicals/1221
Chemicals - Ethylene	New decarbonization technology/process	Catalytic Coating of Coils	Reducing coking can greatly improve heat transfer in furnaces. A novel catalytic coating is applied to the internal surfaces of tubes and coils that can greatly reduce coke formation and also allow higher ethylene selectivity.	Pilot	6% reduction	6-10% reduction				Non peer-reviewed article	http://energy.gov/sites/prod/files/2015/06/f22/1001-High-Value%20Chemicals-061015_FINAL.pdf
Chemicals - Aromatics	New decarbonization technology/process	Lignin to Aromatics	Lignin (mainly from woody biomass) can be used as a feedstock for producing aromatics. Lignin must be first depolymerized and defuncionalized. Energy impact is probably greater, but GHG's associated with life cycle will be lower.	Conceptual	Less	More				Non peer-reviewed article	https://www.iea.org/publications/freepublications/publication/Chemical_Roadmap_2013_Final_WEB.pdf
Chemicals	Current Technology	Steam Reforming Hydrogen Production	Steam and methane combine to create syngas; oxygen is then strippe dfrom water to oxidize CO to CO2.	Current Standard	9 - 12 t CO2 / t Hydrogen						
Chemicals - Hydrogen	New decarbonization technology/process	Photocatalytic Hydrogen Production	Creation of hydrogen from water through photocatalytic processes that already occur in photosynthesis through complex biological reaction pathways. Lots of energy input required, but does not require fossil fuels.	Conceptual	Less	More				Non peer-reviewed article	https://www.iea.org/publications/freepublications/publication/Chemical_Roadmap_2013_Final_WEB.pdf
Chemicals - Ammonia	New decarbonization technology/process	Solid State Synthesis	Solid state ammonia synthesis using electricity	Pilot				New Build Only		Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050
Chemicals - Ammonia	New decarbonization technology/process	Low pressure catalyst for ammonia synthesis	Synthesis of ammonia takes place on an iron catalyst at lower pressure and temperature. Catalysts utilizing ruthenium allow even lower pressure	Early Commercialization	7% Reduction						
Chemicals - Ammonia	New decarbonization technology/process	Biomass gasification to produce syngas	Replacing natural gas feedstock with syngas from biomass for low carbon source of hydrogen for the production of ammonia	Commercial	63% Reduction		300-400 Euros / Mtonne NH3 produced, ~31 Euros/tonne	New Build Only	Sourcing of biomass	Technology Roadmap	http://www.cedelft.eu/publicatie/identifying_breakthrough_technologies_for_the_production_of_basic_chemicals/1221
Chemicals - Chlorine	New decarbonization technology/process	Retrofit ODC for chlorine production	Retrofit Oxygen Depolarised Cathode (ODC) to membrane cells	Small Scale Commercialization	23% reduction	23% reduction				Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

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Chemicals - Styrene	New decarbonization technology/process	Dehydrogenation in carbon dioxide	Carbon dioxide acts as a diluent, shifting and enhancing the equilibrium conversion. The process also improves selectivity and provides improved heat delivery due to high heat capacity.	Pilot	40% Reduction	2.5 GJ/t-styrene, compared to 6.3 GJ/tonne styrene for the current process	Retrofit $US10-15 million (250,000 t/yr plant)			Non peer-reviewed article	https://www1.eere.energy.gov/office_eere/pdfs/exelus_case_study.pdf
Chemicals - Generic	New decarbonization technology/process	Membrane Technology	Deploy membrane technologies to replace more energy intensive separation technologies such as distillation	Pilot	8% reduction	8% reduction				Technology Roadmap	https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050
Chemicals - Generic	New decarbonization technology/process	Use of enzymatic versus chemical catalytic process	Use of fermentation and enzymatic processes instead of chemical processes with catalytic reactions. Biological processes take place at lower temperature and pressures, reducing energy demand by as much as 50%. An example with the greatest potential worldwide is ethylene produced from bioethanol, instead of petrochemical feedstock.	Conceptual		Up to 50% less	$1-5 /tonne of CO2 saved			Peer-reviewed article	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S0734975015300306

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Pulp and Paper											
Pulp and Paper	Biomass and clean electricity	NA	The majority of emissions are associated with heat and steam production, as well as electricity. According to the EPA (see reference), increasing biomass and clean electricity compared to natural gas is the best feasible abatement option.	Commercial						Non peer-reviewed article	https://www.epa.gov/sites/production/files/2015-12/documents/pulpandpaper.pdf
All sectors											
Metal Processing, Iron and Steel, Chemicals, Cement and Glass	New decarbonization technology/process	Chemical Looping Combustion	A combustion process with an oxygen carrier circled between two fluidized bed reactors: an Air Reactor and a Fuel Reactor. Oxygen carrier is oxidized by introduction of air in AR. Gaseous fuel then reacts with oxygen on oxygen carrier in the FR. Carriers are usually a metal (Ni or Fe are common).	Conceptual	95% CO_2 capture	Uncertain				Peer-reviewed article	http://www.sciencedirect.com.proxy.lib.sfu.ca/science/article/pii/S1364032116000319