TRANSITION ACCELERATOR REPORTS
Volume 3 • Issue 1 • January 2021

Pathways to net zero

A decision support tool

The Transition Accelerator

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Smart Prosperity Institute

RELEASE 1.0

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To cite this document:

Meadowcroft, J. and contributors. 2021. Pathways to net zero: A decision support tool. Transition Accelerator Reports Vol. 3, Iss. 1. Pg 1-108 ISSN 2562-6264.

Acknowledgements

Many individuals contributed to the preparation of this report. We would like to acknowledge research and drafting support from staff at the Smart Prosperity Institute, including the efforts of Katherine Monahan, Hossein Hosseini, Colleen Kaiser, Shabnam Khalaj, Nathan Lemphers, Sonia Patel and Derek Eaton. Contributions and feed back were received from staff and researchers associated with the Transition Accelerator, as well as external analysts and stakeholders who took time to read sections of the report and make comments and suggestions.

We acknowledge the work of many pioneering studies of climate policy and GHG abatement in Canada including those of the National Roundtable on Economy and the Environment, the Deep Decarbonization Project, the Smart Prosperity Institute, the Trottier Energy Futures Project, Clean Energy Canada, and others. We were also inspired by the 2019 study 'Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted, and Coordinated International Action', by David Victor, Frank Geels and Simon Sharpe (The Brookings Institution with the support of the Energy Transitions Commission, 2019).

The publication of this report has been made possible through the generous support of the following Canadian charitable foundations:

La fondation McConnell Foundation

EDMONTON COMMUNITY FOUNDATION

IVEY foundation

Distribution: Transition Accelerator Reports are available online at www.transitionaccelerator.ca. Disclaimer: The opinions expressed in this publication are the authors' alone.

ISSN: Transition Accelerator Reports (Online format): ISSN 2562-6264

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Place of publication: The Transition Accelerator, 2603 7th Ave NW, Calgary AB T2N 1A6. Release 1.0

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Executive Summary

Getting to net zero requires major changes in the large-scale systems we use to meet societal needs, including the way we produce and distribute energy, move people and goods, produce and consume food, and build and live within our cities. This report is intended as a decision-support tool and reference document for those tasked with figuring out how to do this. It provides an assessment of different pathways to net zero for eight critical sectors and systems in Canada. The Transition Accelerator will be adding to this work over time, and will update the report periodically.

Given the growing array of suggested greenhouse gas reduction approaches and technologies, it can be challenging for both policy makers and investors alike to decide the most effective course of action. Determining the way forward requires answers to fundamental questions such as: Which approaches represent genuinely viable pathways to net zero greenhouse gas (GHG) emissions and are ready for widescale deployment? Which show promise but require further research, incubating and piloting? And, perhaps most importantly, which are dead-end pathways that may result in short-term incremental GHG reductions but are incompatible with the scale of decarbonization required to achieve net zero emissions, and could lock-in carbon intensive infrastructure?

> Putting a transition approach into practice means accelerating system or sector-level change to deliver net zero and other societal benefits, rather than just trying to secure the lowest cost incremental GHG reductions

In helping answer these questions, this report adopts a transition and an energy system approach. A transition approach examines opportunities to transform the large-scale societal systems or sectors which give rise to our emissions. This requires understanding how these systems operate, the stage of transition achieved in specific systems ('emergence', 'diffusion' or 'system reconfiguration'), and the non-climate-related problems and disruptive currents influencing their evolution. As the latter are often more compelling to the relevant stakeholders than the threat of climate change, integrating low carbon initiatives with solutions to these broader challenges is critical to success. And, since changes large enough to achieve net zero are certain to alter sector norms and the social distribution of costs and benefits, engaging with wider system challenges is unavoidable regardless.

Putting a transition approach into practice means that policy design and investment should be focused on accelerating system or sector-level change - to deliver net zero and other societal benefits - rather than just trying to secure the lowest cost incremental GHG reductions by a specified date. It also means accepting that there is no "one size fits all" solution, although economy wide approaches, notably carbon pricing, can act to encourage change. In most cases, policy needs to be tailored to system or sectoral level considerations and designed for the stage of transition at which it is at. This latter consideration is particularly important. The conventional wisdom amongst many policy-makers in Canada is that while governments have a role to play to support innovation, they should steer clear of 'picking winners' and allow the marketplace to determine the pace and scale of deployment. The transition and energy system approach adopted in this report suggests a different view. History shows governments cannot avoid taking decisions about large-scale technological options – without such commitments in the past we would not have built a national highway system and provincial electricity grids, nor developed nuclear power or the oilsands. To meet the net zero challenge, we need targeted support (R&D, experiments, and demonstration) for promising approaches, and deliberate policy and investment decisions to deploy at scale the solutions that have already emerged. Accelerating change in the systems and sectors where new technologies and practices are available can facilitate movement elsewhere by establishing the profitability of low-carbon investment, showing change is possible and inevitable, and weakening demand for end use fossil fuels.

While it is not possible to fully anticipate technological and economic developments decades in advance, critical elements of what is needed to achieve net zero are already clear.

A transition and energy systems approach also emphasizes the importance of conceptualizing what a viable net zero energy system could look like in the future. Then, by working backwards, it is possible to define the most promising pathways to get there. While it is not possible to fully anticipate technological and economic developments decades in advance, critical elements of what is needed to achieve net zero are already clear. These include:

- decarbonizing electricity generation and expanding electricity supply while electrifying as much of energy end-use as possible
- developing and deploying net zero fuels to replace fossil fuels in situations where electrification is difficult or expensive
- enhancing energy efficiency to reduce the new net zero energy needed to meet demand
- addressing non-energy emissions (waste, industrial processes, and agriculture), and
- testing and deploying carbon removal approaches to offset residual emissions.

This report assesses technologies and approaches that can contribute to building transformative pathways in eight critical sectors and systems: electricity; transport (cars, heavy trucks); buildings; heavy industry (oil and gas, mining, cement); and agri-food. It identifies critical areas where policy and investment can accelerate the diffusion and scale-up of specific technologies and practices. In sectors where solutions are not yet mature, it identifies areas for accelerating research, pilot projects, and large-scale experiments to prepare for future mass deployment.

For electricity this means accelerating full decarbonization of the sector (coal phase out, replacing unmitigated gas with renewables and other zero-emission options); improving system capacity to integrate and deliver affordable, resilient net zero electricity (regional interties, storage, grid improvements, demand management, etc.); and incrementally expanding generation to handle increased loads from the electrification of transport and other sectors. Priorities differ by province. Over the medium-term, electricity/hydrogen integration can enable a fully net zero energy supply.

For transport it means encouraging a rapid transition to electric (light and medium duty) vehicles and the build out of the zero-emission vehicle supply chain in Canada. The bulk of this shift could be achieved in 10-15 years, with huge economic consequences for Canada depending on whether the country becomes an international leader or a laggard. The encouragement of active mobility and the continued extension and upgrade of electrified mass transit systems are also important. Heavy freight requires the development, demonstration, and subsequent rollout of practical solutions (such as hydrogen fuel cell trucks and trains).

For buildings it implies measures to improve the performance of all new construction (i.e., strengthened performance-oriented building codes), as well as the systematic roll-out of programs to upgrade existing structures so the whole building stock can meet net zero standards. This includes large-scale retrofits tied to new financial models to attract private capital. For heating, electric options are already practical, and research, development, and pilots for hydrogen (and in some case renewable gas) need to be accelerated.

For heavy industry solutions vary by sub-sector, depending on the nature of their product, energy demand and process emissions. Defining trajectories for specific industries that dramatically curtail emissions (through fuel shifts, process improvements, output changes, etc.) is a first step. But then the technological innovations and business model adjustments must be carried forward in practice and at scale as solutions reach maturity.

For agriculture immediate efforts can be made to reduce emissions from nitrogen fertilizers, improve livestock management, and encourage soil carbon retention through farm practices. But transition in agri-food is at a relatively early phase, and there is a need for additional research, demonstration, practical experiments, and collaborative learning with the farm sector to map out broader transformative pathways.

The report also identifies cross cutting issues, three of which deserve mention. First, the importance of **energy efficiency** – which reduces the low carbon energy supply needed to decarbonize end use sectors (transport, buildings, industry, etc.). Second, **developing hydrogen as a net zero energy carrier** which can find application in multiple sectors, including as energy storage to facilitate deployment of intermittent renewables. And third, **negative emission approaches** where major questions remain regarding technical viability, permanence, scale, and cost. The immediate challenge here is to conduct research, development, and experimentation across multiple sectors, assessing performance, potential, and the circumstances under which these approaches are best deployed.

In policy terms, specific measures are required to accelerate change in each sector and subsector, with multiple instruments integrated into packages to achieve goals appropriate to the transition phase. These will include policies to develop and encourage the uptake of specific technologies, as well to mandate the phase out of fossil fuel dependent technologies and practices. There is also a need for economy-wide policies to encourage transition: carbon pricing at a scale to shift investment and consumer behaviour away from GHG intensive practices and products; low carbon public procurement to strengthen niches for emerging technologies; low carbon finance mechanisms to mobilize capital for transition; support for clean technology research, development, and deployment; and finally, social and policy innovation to accelerate the systems transitions getting underway.

Priorities for key sectors

POWER

9% OF CANADIAN EMISSIONS

DIFFUSION

Multiple low carbon generation options. Will assume transport and other loads as decarbonization progresses.

ACTIONS: Priorities differ by province: Phase out coal; integrate renewables and other net zero sources; Improve system capacity to deliver reliable, affordable net zero electricity (grid interties, storage, demand management)

BUILDINGS

13% OF CANADIAN EMISSIONS

EARLY DIFFUSION

Advanced building approaches and electric heating mature. 'Green gas' options immature. Systematic retrofit of existing structures is critical.

ACTIONS: More stringent codes for new builds; regulatory standards to drive improvement in existing buildings; public procurement to support sector transformation; pilot mass retrofit approaches; develop mechanisms to mobilize private capital for retrofits.

Priorities for key sectors (CONT'D)

CARS

13% OF CANADIAN EMISSIONS

EARLY DIFFUSION

Innovation stabilized around electric vehicles for personal cars and light trucks. Critical to break fossil energy dependence in transport.

ACTIONS: Accelerate EV adoption and build value chain for manufacture of zero emission vehicles. Invest in charging infrastructure. Zero emission vehicle standard. Fix phaseout goal for gasoline cars.

HEAVY TRUCKS

9% OF CANADIAN EMISSIONS

EMERGENCE

Heavy vehicle options require further development to enter market at scale.

ACTIONS: Vehicle development R&D, trials at scale, infrastructure investment, low carbon hydrogen production, zero emission vehicle mandate, public procurement, support for fleet conversions.

OIL & GAS

26% OF CANADIAN EMISSIONS

EMERGENCE

Approaches to net zero fossil fuel production and net zero energy production from fossil resources are immature. Traditional production wind down necessary for net zero.

ACTIONS: Dramatically improve energy efficiency and emissions profile of existing oil and gas extraction. R&D and infrastructure for zero emission fuels production (hydrogen or electricity), geothermal energy, and materials. Scale back all investment in the sector not geared to an ultra-low emission future.

CEMENT

1.5% OF CANADIAN EMISSIONS

EMERGENCE

No single pathway has emerged. Fossil energy can be replaced by electricity, hydrogen, or biofuels. Process emissions can be addressed by CCS or changing cement chemistries. Novel building materials could reduce cement demand.

ACTIONS: R&D and demonstration projects to address energy and process emissions. Changes to procurement and building codes to establish market for low carbon cement.

MINING

1% OF CANADIAN EMISSIONS

EMERGENCE

Electric and hydrogen fuel cell equipment; on-site renewable electricity generation; advances in processing technologies and efficiency; recycle metals and reduce use.

ACTIONS: Support for advanced ore movement and processing technologies. Electrification of operations. Develop low emission mining to service expanded material needs of net zero societies

AGRI-FOOD

10% OF CANADIAN EMISSIONS

EMERGENCE

Approaches to address emissions from animal agriculture and nitrogen fertilizer use are in development. Sustainable farming and food system models remain immature in this diverse sector.

ACTIONS: Research, trials and promotion of alternative crop regimes and technologies to reduce nitrogen fertilizer use, improve manure management and reduce enteric emissions. Encourage production and consumption of alternative proteins. Decarbonize on farm energy use.

Résumé

Si notre objectif est d'atteindre la carboneutralité, il sera impératif d'apporter d'importants changements aux systèmes à grande échelle que nous utilisons pour répondre aux besoins de la société. Ces changements auront une incidence sur la production et la distribution de l'énergie, le transport des personnes et des biens, la production et la consommation des aliments ainsi que la façon dont nous construisons et habitons nos villes. Le présent rapport se veut un outil d'aide à la prise de décision ainsi qu'un document de référence pour les personnes qui auront la responsabilité de choisir la voie à suivre pour la réalisation de cet objectif. Il propose une évaluation de différentes trajectoires susceptibles de permettre à huit secteurs et systèmes de première importance au Canada d'atteindre la carboneutralité. L'Accélérateur de transition contribuera à ces travaux au fil du temps en mettant périodiquement le rapport à jour. Compte tenu du nombre croissant d'approches et de technologies susceptibles de permettre la réduction des gaz à effet de serre (GES), il pourrait s'avérer difficile pour les décideurs et les investisseurs de choisir la façon de procéder qui serait la plus efficace. Définir la voie à suivre exige de répondre à des questions fondamentales comme celles-ci : quelles approches constituent des trajectoires vraiment réalisables qui permettront d'atteindre la carboneutralité et qui sont prêtes pour une utilisation à grande échelle? Lesquelles sont prometteuses mais nécessitent des recherches plus poussées ainsi qu'une période de développement et d'expérimentation plus longue? Et, plus important peut-être encore, quelles sont les voies que l'on peut considérer comme étant « sans issues » parce qu'elles peuvent entraîner des réductions supplémentaires de GES à court terme, mais qu'elles sont incompatibles avec l'ampleur de la décarbonisation requise pour éliminer toute émission et qu'elles pourraient de surcroît constituer un obstacle à la transition des infrastructures à forte intensité de carbone?

> Mettre en œuvre une approche fondée sur la transition consiste à accélérer les changements à l'échelle du système ou du secteur en vue d'atteindre la carboneutralité et bénéficier d'autres avantages sociétaux, une démarche qui va bien au-delà de la simple recherche de réductions supplémentaires de GES au moindre coût possible.

Pour aider à répondre à ces questions, le présent rapport a choisi une approche axée sur la transition et le système énergétique. Une telle approche étudie les possibilités de transformer les systèmes ou les secteurs sociétaux utilisés à grande échelle qui génèrent nos émissions. Pour ce faire, elle cherche à comprendre la façon dont ces systèmes fonctionnent, à déterminer le stade de transition atteint

par des systèmes spécifiques (« émergence », « diffusion » ou « reconfiguration du système »), et à déceler les problèmes et courants perturbateurs qui ne sont pas liés au climat mais qui influencent l'évolution de ces systèmes. Ces éléments perturbateurs constituent d'ailleurs souvent des arguments plus convaincants pour les parties prenantes concernées que la menace des changements climatiques. Il est donc essentiel, si l'on veut remporter un quelconque succès, d'intégrer des initiatives à faibles émissions de carbone dans les solutions apportées à ces plus grands défis. L'atteinte de la carboneutralité exigera des changements de grande envergure qui ne manqueront pas de modifier les normes du secteur concerné ainsi que la répartition sociale des coûts et des bénéfices, ce qui nous obligera inévitablement à relever des défis systémiques de plus grande ampleur.

S'il est impossible de complètement prévoir les développements technologiques et économiques qui surviendront au cours des prochaines décennies, nous connaissons déjà les éléments essentiels des mesures qui doivent être adoptées pour atteindre la carboneutralité.

Mettre en œuvre une approche fondée sur la transition consiste à concevoir des politiques et à faire des investissements qui visent à accélérer les changements à l'échelle du système ou du secteur, et ce, dans le but d'atteindre la carboneutralité et de bénéficier d'autres avantages sociétaux. C'est une démarche qui va bien au-delà de la simple obtention, à une date donnée, de réductions supplémentaires de GES au moindre coût possible. Cette approche implique également d'accepter qu'il n'existe pas de solution « universelle », même si certaines mesures appliquées à l'échelle de l'économie, telles que la tarification du carbone, peuvent contribuer à accélérer le processus de changement. Dans la plupart des cas, la politique doit être adaptée pour tenir compte de la situation particulière du système ou du secteur concerné, et être conçue pour correspondre au stade de transition que celui-ci a atteint. Cette dernière remarque revêt une importance particulière. En effet, tout en reconnaissant que les gouvernements ont un rôle à jouer pour soutenir l'innovation, de nombreux décideurs au Canada adhèrent au cliché selon lequel les gouvernements devraient s'abstenir de « choisir les gagnants » et permettre plutôt au marché de déterminer le rythme et l'ampleur de la mise en œuvre des nouvelles solutions. L'approche axée sur la transition et le système énergétique, qui a été privilégiée dans le présent rapport, propose un point de vue différent. L'histoire montre que les gouvernements sont dans l'obligation de prendre des décisions en ce qui concerne les possibilités technologiques utilisées à grande échelle; sans de tels engagements pris dans le passé, nous n'aurions pas construit un réseau routier national et des réseaux d'électricité provinciaux, ni développé l'énergie nucléaire ou exploité les sables bitumineux. Pour atteindre l'objectif de la carboneutralité, il est nécessaire d'apporter un soutien ciblé aux approches qui sont prometteuses (R et D, expérimentation et démonstration) et de prendre des décisions en matière de politiques et d'investissements qui visent sciemment à promouvoir la mise en œuvre à grande échelle des solutions qui sont déjà connues. L'accélération des changements dans les systèmes et les secteurs où de nouvelles technologies et pratiques sont disponibles peut faciliter la transition ailleurs, et ce, de trois façons : en démontrant la rentabilité des investissements dans les solutions à faibles émissions de carbone, en montrant que le changement est non seulement possible mais qu'il est inévitable, et, enfin, en réduisant la consommation des combustibles fossiles à utilisation finale.

S'il est impossible de complètement prévoir les développements technologiques et économiques qui surviendront au cours des prochaines décennies, nous connaissons déjà les éléments essentiels des mesures qui doivent être adoptées pour atteindre la carboneutralité.

Une approche axée sur la transition et le système énergétique souligne également l'importance de concevoir la forme future que pourrait avoir un système énergétique qui soit à la fois carboneutre et réalisable. Ensuite, en procédant dans l'ordre inverse, on pourrait définir quelles trajectoires sont les plus prometteuses pour le concrétiser. S'il n'est pas possible de complètement prévoir les développements technologiques et économiques qui surviendront au cours des prochaines décennies, nous connaissons déjà les éléments essentiels des mesures qui doivent être adoptées pour atteindre la carboneutralité. Ceux-ci comprennent notamment :

- La décarbonisation de la production d'électricité, l'accroissement de l'approvisionnement en électricité et l'électrification la plus généralisée possible de la consommation finale d'énergie;
- Le développement et l'utilisation à grande échelle de combustibles sans émission pour remplacer les combustibles fossiles dans les situations où l'électrification est difficile et coûteuse à réaliser;
- L'amélioration de l'efficacité énergétique afin de réduire la quantité de nouvelle énergie sans émission nécessaire pour satisfaire à la demande énergétique;
- La lutte contre les émissions qui ne sont pas liées à l'énergie (déchets, procédés industriels et agriculture) et
- L'expérimentation et l'utilisation à grande échelle des approches permettant l'élimination du carbone dans le but de compenser les émissions résiduelles.

Le présent rapport évalue les technologies et les approches susceptibles de contribuer à la création de trajectoires de transformation pour huit secteurs et systèmes de première importance, soit ceux de l'électricité, des transports (voitures, camions lourds), des bâtiments, de l'industrie lourde (pétrole et gaz, mines, ciment) ainsi que de l'agroalimentaire. Il précise dans quels domaines essentiels les politiques et les investissements peuvent accélérer la diffusion et l'utilisation à plus grande échelle de technologies et de pratiques particulières. En ce qui a trait aux secteurs où le développement des solutions n'est pas terminé, il indique les domaines susceptibles d'accélérer la réalisation de recherches, de projets pilotes et d'expérimentations à grande échelle, dans le but de préparer la future mise en œuvre massive de ces solutions.

Pour le secteur de l'électricité, les mesures à mettre en application consisteront à accélérer la décarbonisation complète du secteur (élimination progressive du charbon, remplacement par des énergies renouvelables du gaz qui ne fait pas l'objet de mesures d'atténuation et adoption d'autres solutions sans émission); à améliorer la capacité du système à intégrer et fournir de l'électricité sans émission qui soit abordable et fiable (grâce aux interconnexions régionales, au stockage de l'électricité, à l'amélioration du réseau, à la gestion de la demande, etc.); et, enfin, à augmenter progressivement la production pour répondre à une demande accrue découlant de l'électrification des transports et d'autres secteurs. Les priorités diffèrent cependant d'une province à l'autre. À moyen terme, l'utilisation intégrée de l'électricité et de l'hydrogène rendra ainsi possible un approvisionnement énergétique sans aucune émission.

Pour le secteur des transports, il s'agira de promouvoir une transition rapide vers les véhicules électriques (de poids léger et moyen) et de soutenir la construction de la chaîne d'approvisionnement des véhicules sans émission au Canada. La majeure partie de ces changements pourrait être réalisée sur une période de 10 à 15 ans, et les conséquences économiques pour le Canada, qui seront énormes, varieront selon que le pays deviendra un chef de file au niveau international ou, au contraire, un retardataire dans le domaine. Il sera également très important d'encourager la mobilité active et de soutenir l'extension et la modernisation continues des systèmes électrifiés de transport en commun. La transformation du fret lourd exigera, quant à elle, le développement, la démonstration et l'utilisation ultérieure de solutions pratiques (telles que les camions et les trains à pile à hydrogène).

Pour le secteur du bâtiment, il sera nécessaire de mettre en œuvre des mesures visant à améliorer la performance de toutes les nouvelles constructions, c.-à-d. adopter des codes du bâtiment plus stricts et axés sur la performance. Il faudra également offrir de manière systématique des programmes de mise à niveau des structures existantes dans le but de permettre à l'ensemble du parc immobilier de respecter les normes en matière de carboneutralité. Cela comprendra des rénovations à grande échelle associées à de nouveaux modèles financiers permettant d'attirer des capitaux privés. En ce qui concerne le chauffage, les options électriques sont déjà disponibles; pour l'hydrogène (et dans certains cas le gaz renouvelable), il sera nécessaire d'accélérer la recherche, le développement et la réalisation de projets pilotes.

Pour l'industrie lourde, les solutions varieront selon le sous-secteur, en fonction de la nature du produit, de la demande d'énergie et de la quantité d'émissions générée par le procédé utilisé. La première étape consistera à définir, pour des industries particulières, des trajectoires permettant de réduire considérablement leurs émissions (grâce au passage à un autre type de carburant, à l'amélioration des procédés utilisés, à la modification de la production, etc.). Il faudra ensuite ajuster le modèle d'entreprise et poursuivre les innovations technologiques, en pratique et à grande échelle, à mesure que les solutions technologiques arriveront à maturité.

Pour l'agriculture, il est possible d'adopter des mesures immédiates permettant de réduire les émissions provenant des engrais azotés, d'améliorer la gestion du bétail et de favoriser la rétention du carbone dans les sols à l'aide de pratiques agricoles adaptées. La transition dans le secteur agroalimentaire n'en est cependant qu'à une phase relativement précoce; pour tracer des trajectoires de transformation plus générales, il sera donc nécessaire d'effectuer des recherches, des démonstrations et des expériences pratiques supplémentaires, en veillant à créer des occasions d'apprentissage collaboratif avec le secteur agricole.

Le rapport définit également différentes problématiques transversales, dont trois méritent une mention. La première concerne l'importance de **l'efficacité énergétique** qui permet de réduire la quantité d'énergie à faibles émissions de carbone nécessaire pour décarboner les secteurs d'utilisation finale (transports, bâtiments, industrie, etc.). La deuxième a trait au **développement de l'hydrogène en tant que vecteur énergétique sans émission**; ce combustible peut en effet trouver une application dans plusieurs secteurs et permettre, entre autres, de stocker l'énergie en vue de faciliter l'utilisation d'énergies renouvelables intermittentes. Enfin, la troisième problématique est liée aux **approches d'émissions négatives**, dont la mise en œuvre soulève d'importantes questions, notamment en ce qui concerne leur viabilité technique, leur permanence, leur coût et l'échelle à laquelle elles peuvent être utilisées. Dans ce contexte, le défi immédiat à relever consiste à mener des activités de recherche, de développement et d'expérimentation dans plusieurs secteurs, et à évaluer les performances et le potentiel de ces approches ainsi que les circonstances dans lesquelles elles pourraient s'avérer le plus utiles.

En ce qui concerne les politiques, il sera impérieux d'adopter des mesures spécifiques pour stimuler l'accélération des changements dans chaque secteur et sous-secteur. Pour ce faire, on constituera des ensembles de mesures, intégrant de multiples instruments, qui permettront d'atteindre des objectifs adaptés à la phase de transition à laquelle se trouve le secteur ou sous-secteur concerné. Ces mesures comprendront des politiques qui visent à développer et encourager l'adoption de technologies spécifiques, tout en imposant l'élimination progressive des technologies et pratiques qui dépendent des combustibles fossiles. Pour favoriser la transition, il sera également nécessaire de mettre en œuvre des politiques à l'échelle de l'économie dans son ensemble. Parmi celles-ci, mentionnons une tarification du carbone appliquée à une échelle qui incite les consommateurs et les investisseurs à changer leur comportement et à abandonner les pratiques et les produits à forte intensité de GES; des politiques d'approvisionnement public encourageant l'adoption des solutions à faibles émissions en vue de soutenir la niche commerciale des technologies émergentes; des mécanismes permettant de financer les solutions à faibles émissions afin de mobiliser les capitaux pour la transition; le soutien à la recherche, au développement et à l'utilisation à grande échelle des technologies propres; et, enfin, l'innovation sociale et politique afin d'accélérer les transitions de systèmes qui sont en cours de réalisation.

1. Introduction

The purpose of this report is to provide a simple tool to help those concerned with policy and investment decisions to achieve net zero greenhouse gas (GHG) emissions in Canada. It provides a high-level analysis of potential pathways, evaluating alternatives and assessing advances made in building them out. For too long discussion of climate policy in Canada has assumed that we should move forwards by doing a little of everything. But the time has come to identify priority elements that can accelerate real change.

The report adopts a transition and energy systems approach. Rather than focusing narrowly on emissions, it examines opportunities to transform the large-scale societal systems which give rise to these emissions. Today, major systems of social provisioning — the way we move people and goods, construct buildings, produce food, operate industry, and so on – remain dependent on fossil fuels. Shifting these sectors onto more sustainable trajectories is at the core of the net zero challenge. This requires an understanding of how existing systems operate, and the non-climate-related problems and disruptive currents influencing their evolution. So, the focus of this report is not 'tons to target' (although ultimately the math must add up!), but on transforming key systems into configurations compatible with net zero goals.

For too long discussion of climate policy in Canada has assumed that we should move forwards by doing a little of everything. But the time has come to identify priority elements that can accelerate real change.

The high-level analysis presented here is intended to complement the more detailed and 'ground-up' regional and sector pathway building efforts undertaken by the Transition Accelerator and other societal actors, and more comprehensive quantitative assessments. In the full sense, a transition 'pathway' describes the sequence of multi-dimensional changes (to technologies, business strategies, policy and regulatory frameworks, social practices, financing, and so on) required to transform a system. Such pathways are detailed and context dependent, and in Canada will differ from region to region. Here we are concerned less with fine-grained analysis, and more with the broad-brush strokes – the major technical and social elements which can anchor transformative change, and the actions which can accelerate their deployment.

For the purposes of this report we understand 'net zero' to imply a society where any remaining GHG emissions are counter-balanced by removals.a Since removal technologies involve many uncertainties, we emphasize reducing sector emissions towards zero, leaving the smallest residual to be handled though removals. Looking forward to mid-century we assume that Canada will continue to experience economic and population growth roughly along the lines of recent decades. And Canada's movement towards net zero is understood in the context of a coordinated international effort, even if progress across countries remains uneven.

The evaluation presented here is based on a review of existing literature and consultation with experts. It presents an initial examination of transition pathways, highlighting the most important sectors and promising trends. Not all systems and sectors are covered or are covered in the same detail. Although the report draws on publicly available modeling work, it does not involve a specific modelling exercise. Its focus is rather to identify the broad avenues of advance and their potential to deliver net zero emissions along with other societal objectives.

In the coming months we expect to deepen work on specific sectors, adding more topics and issues. We also intend to update this report periodically. The relative appeal of different options may shift with technological, social, economic, and political change. And it is important to monitor progress along specific pathways over time. These updates will also provide the opportunity for more systematic consultation with a wider range of experts and stakeholders.

The analysis presented here represents our best effort to systematize current understanding, but it is inevitably incomplete and imperfect. So, we welcome commentary and feed-back that can sharpen the analysis and rectify mistakes.

Through this engagement we seek to contribute to the broader societal debate about the net zero challenge and the contours of the Canada we wish to see emerge over coming decades.

The report is organized into two parts. The first deals with our basic approach, outlining what we mean by a 'transition' and 'energy system' perspective, and briefly examining the issues of non energy related emissions and GHG removals. The second presents the analysis of specific system/ sector pathway elements.

2. Accelerating system transitions

Getting to net zero will require major changes in the large-scale systems we use to meet societal needs, including the way we produce and distribute energy, move people and goods, and build our cities.[1,2] Although change in such systems is typically incremental, there have been many dramatic transformations in the past: consider the emergence of a transport system based around the personal automobile,[3] the build-out of electricity systems to provide power for homes and businesses,[4] or the ways computing and the digital economy are altering how we live today. These 'system transitions', which may take several decades, involve interconnected changes to technologies, social practices, business models, regulations and societal norms.[3,5,6]

Transitions are periods of considerable uncertainty, since it is unclear how fast change will come and which approach will pan out. They often have significant distributional impacts.[7] While society may benefit from system change that offers increased service and economy, some enterprises or sectors will contract even as emergent firms and industries expand. Incumbents resist change, and this makes progress bumpy.[8,9] Moreover, there are always multiple ways to apply new technologies, social practices, or business models – that articulate different values and/or provide alternative distributions of benefit. So, transitions inevitably involve struggles over the direction and pace of change.[10,11]

It is no surprise, then, that governments, politics, and policy play an important role in system transitions.[12,13] States may see strategic, military, or commercial advantage in emergent technological systems (consider the development of steam ships, satellites, or the Internet). Changes to regulatory frameworks and property rights are normally required to unleash the potential of new approaches. And actors linked to established and emerging industries contend to influence the direction of policy.

Transitions typically pass through three basic stages: 'emergence', 'diffusion', and 'system reconfiguration'.[14] Emergence is about developing and testing alternatives. Dissatisfaction with the established way of doing things spurs innovators to experiment. At first new technologies are expensive and imperfect, and the designs and business models that will allow widespread adoption are unclear. Novel solutions typically emerge in protected niches – where users are willing to pay over the odds and ignore functional shortcomings. Solar cells, for example, found early applications generating power for spacecraft and in remote locations. As innovators gain experience with the new technology, a combination of favorable circumstances (problems with the existing regime, changes in political or economic context) may allow a more direct challenge to the status quo.[15,16]

During the diffusion phase the new approach gains adherents, improves functionality, and prices fall with economies of scale. Positive feedback loops kick in as consumers become increasingly familiar with the new approach, infrastructure is built out, complementary innovations come to market, and more favorable policy and regulatory frameworks are put in place. As this phase advances, incumbents may become increasingly alarmed by the rapid progress of the challengers and very public struggles may emerge.[17,18]

Eventually, change impacts the overall configuration of the system: sometimes the novel elements are incorporated through realignment, while important features of the previous system remain, but on other occasions a new system almost entirely replaces the old. With this reconfiguration, regulatory and policy frameworks become fully aligned with the new arrangements, linkages to other systems are stabilized, and challengers become the new incumbents.[19,20] These three phases trace out a classic S curve, where a long preparatory phase gives way to widespread deployment and ultimately system transformation (see **Figure 1**).

Approaching the climate challenge from the perspective of system transitions brings to the fore issues that can help the design of transformational pathways and the formulation of supportive policy. In the first place, while it is common to talk about 'the low carbon transition' or 'the energy transition', decarbonizing the economy will actually involve a series of inter-related transitions in an array of sectoral systems (personal mobility, freight movement, agri-food, and so on) [1,2]. Each of these sectors has distinctive dynamics and different obstacles and enabling factors. Moreover, climate change is not the only problem, nor is it typically the most powerful driver of change.

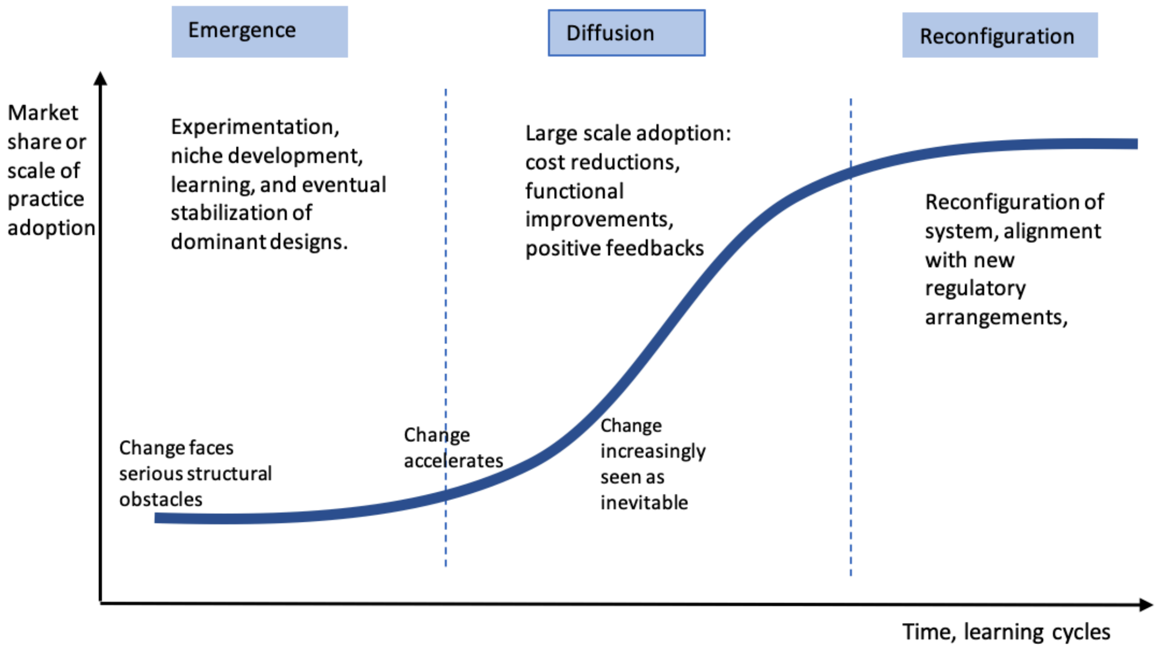


Figure 1. Typical S curve of technology or practice adoption and system transition

Adapted from Victor, Geels and Sharpe, 2019

Some sectors are already being disturbed by powerful disruptive currents (consider autos with electric and autonomous vehicles and ride-hailing apps).[21–23] Integrating low carbon initiatives with solutions to broader challenges is therefore critical. And, since changes big enough to achieve net zero are certain to alter sector norms and the social distribution of costs and benefits, engaging with wider system challenges is unavoidable.

Other policy implications of a transition approach to reaching net zero are that:

- **Accelerating system changes that achieve net zero (and other societal objectives) should be the focus of policy design,** rather than trying to secure the lowest cost incremental GHG reductions by a specified date. In many cases the cheapest or most obvious abatement opportunities are not part of a transformational pathway, and investing in them wastes time and resources that can better be devoted to more strategic efforts.
- **Policy should be attuned to the particularities of the sector and region under consideration.** Only in this way can it empower innovators and target the specific barriers that are preventing change. Agri-food, personal mobility and buildings involve different technologies, actors, and regulatory frameworks, and specific pathways and policy supports are required in each context.
- An **understanding of transition phases (emergence, diffusion, reconfiuration) can help guide the design of the policy mix** at each stage of the transformational process (see Box A). A vast array of policies including R&D support, regulations, tax measures, subsidies and public education can be applied. At a certain point, phase-out measures, which include retirement dates for specific processes, fuels, or technologies, as well as 'just transition' measures to compensate those disadvantaged by change will be required.
- **Innovation policy should be built around core policy goals, including building a net zero economy (it should be 'mission' or 'challenge driven'),[176] rather than simply establishing a generic framework to encourage all innovation**. Indeed, some innovations may be actively driving us in the wrong direction.
- At the appropriate moment **governments must be prepared to back particular technologies, and social and business practices that can accelerate net zero pathways.** Although there is understandable hesitation about 'picking winners', at a certain point it is necessary to focus investment on the most promising options, fund critical infrastructure, reduce uncertainty for private investors, and facilitate economies of scale. Despite the rhetoric about 'letting the market decide' governments have always made choices about technological options – especially large-scale energy technologies. If they had not done so in the past there would be no trans-Canada highway network, nuclear power industry, oil sands development, and so on.[12,13,24,25]
- While **international factors** (including climate agreements, technological advances, globally integrated supply chains, geopolitical rivalries and trade tensions) will impact the pace and orientation of change in key sectors, national governments still retain powerful levers to influence development trajectories.[12,25]

BOX A

Focusing policy to accelerate change at different transition phases

EMERGENCE

POLICY GOAL: encourage emergence of alternatives that can potentially lead to system transformation capable of delivering net zero GHG emissions and other societal goals.

POLICY APPROACH: support portfolio of R&D focused on particular sector/problems; fund experiments and demonstration programs; articulate visions of the most promising alternatives to coordinate actors; facilitate knowledge sharing across target sectors; fund intermediary actors to network innovators and develop best practices; encourage early application niches (for example, through public procurement).

DIFFUSION

POLICY GOAL: accelerate improvement and large-scale deployment of novel approaches that can lead to positive system transformation

POLICY APPROACH: encourage economies of scale, 'learning by doing', and the availability of complementary technologies; support development of standards and codes; support build out of core infrastructure; stimulate demand with purchase subsidies and public procurement; mobilize investment with grants, loans, tax incentives; apply regulations and fiscal measures to raise pressure on incumbents and create market opportunities for new entrants; conduct public education; assist those disadvantaged by changes or less able to enjoy collective benefits

RECONFIGURATION

POLICY GOAL: carry through the transformation of the system to achieve net zero and other societal objectives

POLICY APPROACH: stabilize new institutional and regulatory frameworks; encourage complementarities with other systems; phase out old system elements including compensation, retraining, regional development.

3. An energy systems perspective

An energy systems perspective, that tracks energy and related material flows through the economy, casts important light on critical features of the net zero challenge. Energy systems involve the harvest of renewable and non-renewable environmental resources (crude oil, uranium, wind, solar radiation, etc.), the conversion of energy into useful forms (gasoline, diesel, electricity), transport to where it is needed (by rail, pipeline or electricity grids), to drive the devices (cars, furnaces, lights) which deliver services (transport, heat, light) to end users (individuals, households, businesses).[26]

The largest sources of primary energy exploited in Canada today are fossil fuels (coal, oil and natural gas), uranium, rivers that generate hydroelectricity, as well as some biomass, wind and solar.[27] Coal is used for electricity production, to provide industrial heat, and (as coke) as a reducing agent in metallurgy. Oil is refined into fuels for transport and industry (and some electricity generation) or for non energy products (chemicals, plastics, lubricants, asphalt etc.). Natural gas contributes to electricity production, heating for industrial processes and in commercial and residential settings, fertilizer production, and it is used within the energy sector itself (for example, in the oil sands). Uranium is converted into fuel for nuclear power plants. Biomass is mainly used for electricity production in the pulp and paper sector, to make liquid biofuels for transport. Electricity generated from hydro, wind, solar, nuclear and gas or oil powers residential, commercial, and industrial end-uses such as lighting, cooling, heating, motors, compressors, steel making and aluminum smelting.[125]

Ultimately, consumers value energy for the wide range of services it provides. At the same time, energy producers have become a significant component of the Canadian economy, providing jobs, export earnings and investment opportunities. And that is an important consideration for developing transition pathways.

Among the most important features of Canada's energy system are that:[28,29]

- the country is a large net energy exporter: producing far more energy than it uses. In 2018 Canada exported 84% of its oil production and 46% of natural gas production to the United States. International exports of uranium, metallurgical coal, and electricity are also significant (85%, 53% and 9% of Canadian production respectively).
- the greenhouse gas intensity of the Canadian economy is high in comparison to that of many other developed countries. Exploiting Canada's comparative economic advantages (abundant land and natural resources) over the past century has led to great prosperity but has left legacy challenges as we move into a carbon constrained world.
- electricity supply systems are already substantially decarbonised, with approximately 80% of generation coming from low carbon sources (principally hydro and nuclear).
- the energy systems of Canadian provinces are highly diverse. Contrasting resource endowments and economic development trajectories, combined with decentralized

constitutional arrangements, have led to different energy profiles. Provincial electricity systems have varied generation assets, ownership structures and regulatory regimes. Electricity has served as a lever for regional economic development, and provinces are hesitant to integrate with neighbouring jurisdictions. Indeed, with the pull of markets to the south, north/south electricity trade is more developed than east/west connections.

This last point — regional variation — conditions the first three features of Canada's energy system described above, for exports differ by province, as do greenhouse gas intensities of GDP, and the GHG intensity of electricity production (see **Figure 2**).

From the perspective of analysing the transition of the energy system in Canada, the following features of the current system are worth bearing in mind:

- the critical dependence of most sectors on end-use combustion of fossil fuels, including almost the entire transportation system, much of the heating in residential and commercial buildings, and various major industries (see **Figure 3**).[30]
- the significant energy losses across the system, including the energy consumed by the oil and gas industry itself, combustion losses (shed as heat in internal combustion engines and thermal power generation), and end use inefficiencies (for example, poorly insulated buildings).[29]
- the relatively centralized nature of fuel and electricity production, where a few main nodes (oil refineries, electric power plants) feed energy through networks to millions of consumers

Jurisdiction	GHG emissions			Value of energy exports: millions of Canadian dollars				
	Tonnes per capita	Tonnes per million dollars of GDP	Grams per kilowatt hours of electricity generated	Oil	Natural gas, gas liquids	Coal	Electricity	Uranium
Newfoundland	19.9	312	26	4,285				
PEI	12.1	301	4					
Nova Scotia	16.4	395	720		29			
New Brunswick	18.7	436	290		3		120	
Quebec	9.4	204	1		46		1301	
Ontario	11.3	208	29		401		517	
Manitoba	16.2	325	1	190			421	
Saskatchewan	67.7	910	680	2,178	90	1	6	910
Alberta	64.3	810	630	22,297	6,366	120	6	
British Columbia	12.6	242	12			5237	623	
Canada	19.6	510	120	35,697	9,283	5358	2995	910

Figure 2. Diversity of Canadian provincial energy systems illustrated through GHG emissions (per capita, per unit of GDP and per unit of electricity generated) and the economic value of key energy exports (2017)

Sources: National Inventory Report 1990-2018: Greenhouse Gas Sources and Sinks in Canada (Canada's Submission to the United Nations Framework Convention on Climate Change); Provincial and Territorial Energy Profiles, Canada Energy Regulator; Environment and Climate Change Canada – National Inventory Report and Statistics Canada.[173]

- the necessity for real-time balancing of supply and demand in electricity systems which becomes an increasing challenge as more variable generation (wind, solar) is integrated onto the grid.[31,175]
- the significance of spatial distribution: oil or wind can only be harvested where they are found, which may be far from markets, and infrastructure constraints (pipeline and electricity grid congestion) matter.
- there is no ideal form of energy: all have a mix of costs and benefits (economic, social, environmental) that must be assessed and balanced.[31]

Political-economic dimensions of Canada's energy system that pose challenges for the transition to net zero include:

- the weight of the oil and gas industry in the economy and public decision making especially in specific regions (jobs, investment portfolios, political influence)
- substantial (and constitutionally protected) provincial control over resources development which makes policy harmonization across the federation difficult
- close economic integration with the United States (with its on-again/off-again climate policy) which must be a consideration in policy making.

An energy system perspective can also tell us something about the net zero GHG-emission energy systems of the future. While we cannot anticipate technological or economic developments decades in advance, some basic parameters are clear.[126,127,128] And knowing something about where we need to end up is important for defining pathways to get there.

A conceptual model of a net zero emission energy system for Canada is presented in **Figure 4**. There are five essential elements of this system:

1. At its heart is a greatly enhanced role for decarbonized electricity in delivering end-use services, particularly for transport, heating of buildings, and industrial operations.[124,126] Electricity is the most versatile of current energy forms and can be efficiently converted to a wide range of uses. Society is already wired-up through the grid. In Canada electricity is 80% decarbonized and we know multiple ways to generate more net zero electricity, including hydro, wind, solar, biomass, other renewables, nuclear, and fossil fuels with carbon capture and storage (CCS).
2. Hydrogen serves as an additional energy carrier in sectors where electrification is difficult or expensive (for example, heavy freight transport and heating), and as a fuel or feedstock for industry.[130,206] Hydrogen can also serve as an electricity storage medium potentially facilitating the deployment of renewables.[126,129]
3. Biofuels will have applications in industry, buildings, agri-food and some transport markets (for example aviation fuel). But issues with feedstocks (and competition from other land uses) may limit their contribution. Should biomass be required for negative emissions through bio-energy carbon capture and storage (BECCS), its role might be expanded.
4. Any remaining domestic uses of fossil energy, including the fossil fuel extraction and processing industries, incorporate low carbon energy, CCS and negative emissions to achieve net zero. Any

fossil fuel exports, and/or energy exports originally derived from fossil sources (for example, hydrogen or electricity), will have net zero production profiles.

5. Dramatic changes in technologies, business models and social practices in the end-use sectors — including substantial increases in energy efficiency[124] — (not shown in Figure 4) will be required to enable the phase out of distributed fossil fuel end-use in transport, buildings, and industry. Many of these changes are discussed in later sections of this report.

It is not possible today to be precise about the relative importance of the elements in this conceptual schema. Technological developments, the evolution of relative costs, social acceptance, international circumstances, and political choices will influence future deployments. How much hydro, versus nuclear, wind, solar and so on will there be in the electrical mix? What proportion of energy needs in each end-use sector will be provided by electricity versus hydrogen? What proportion of hydrogen will come from electrolysis, or from methane reforming with CCS and offsets? How centralized or decentralized will energy provision be? What scale of (net zero production emission) fossil energy exports will remain? Which negative emission approaches will prove viable? Answers to these and many any other questions remain to be determined. The structure of existing systems places significant constraints on likely outcomes. And modelling can help explore the range of possibilities. But these issues will ultimately be resolved by technological, economic, social and political processes.

Despite these uncertainties, several things are clear:

- the relative significance of elements in the schema will vary across Canada, depending on the provincial resource base and economic trajectory, and there are opportunities for provinces to exploit their comparative advantages in developing distinctive low carbon trajectories (hydro serves for energy storage in Quebec, hydrogen can be produced cheaply from methane in Alberta, Saskatchewan has important uranium reserves, etc.).[32]
- since end-use energy requirements are to be shifted from fossil fuels to electricity then we will ultimately need greater electricity supply. Moreover, the growth of population and economic activity over several decades will leave us with more needs to service. Thus, even though some Canadian provinces currently have electricity surpluses, additional centralized or decentralized net zero supply will eventually be required.
- as new generation capacity always imposes costs (economic, social, or environmental), improving efficiency in many end-use sectors (for example buildings) will be important.
- since it does not appear practical to electrify everything, we will need some zero carbon fuel options.[131,132] Enhancing research and development, demonstration projects, and infrastructure investment for hydrogen is therefore urgent. Attention to other potential net zero energy carriers such as advanced biofuels and ammonia is also warranted.
- to accelerate change in the energy system we need to increase the demand for low carbon energy through the transformation of end-use sectors. These transition pathways are explored in more detail later in this report.

SCHEMATIC OVERVIEW OF CANADA'S CURRENT ENERGY SYSTEM

Secondary flows omitted for simplicity (for example: energy from waste)

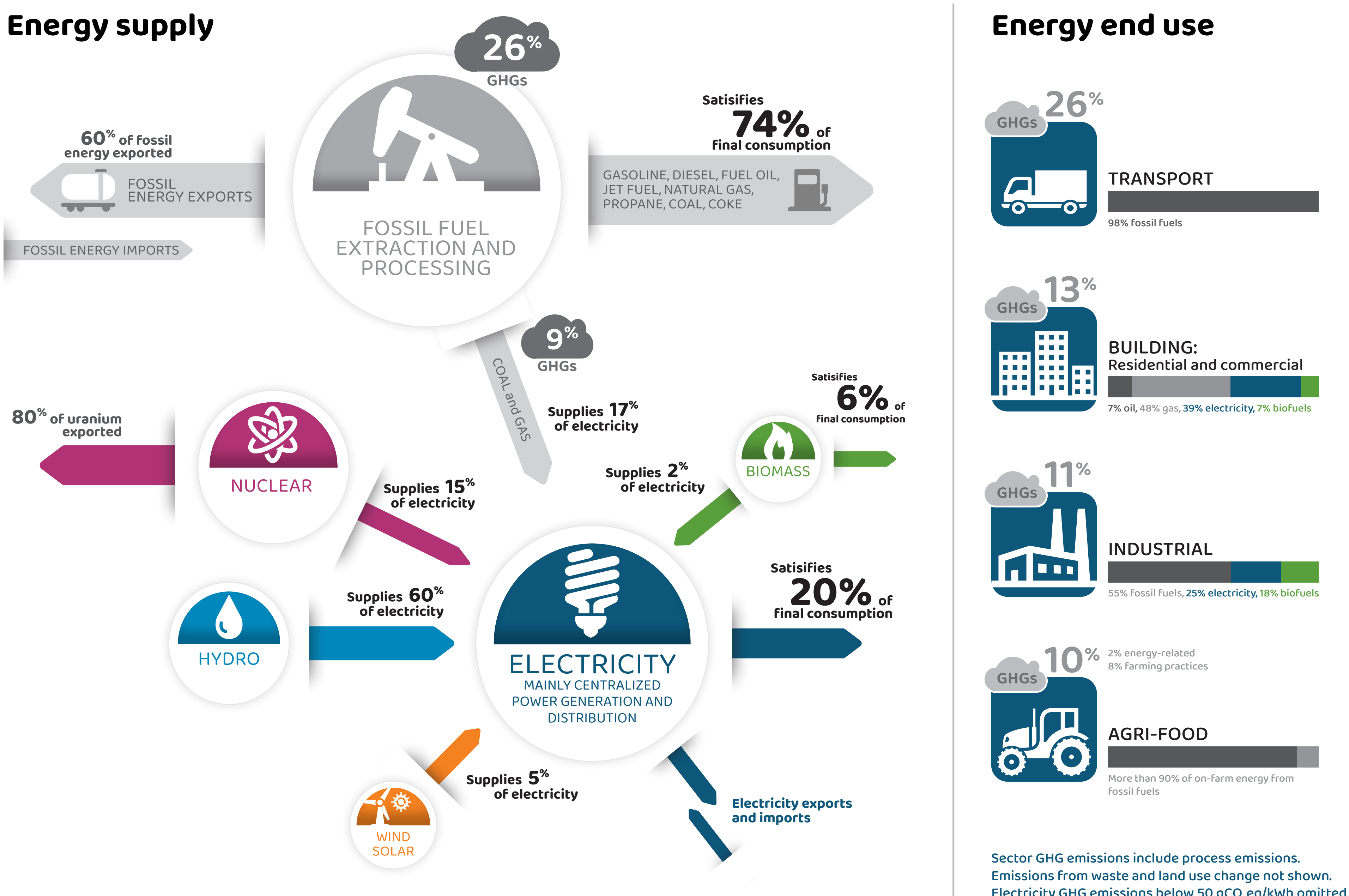
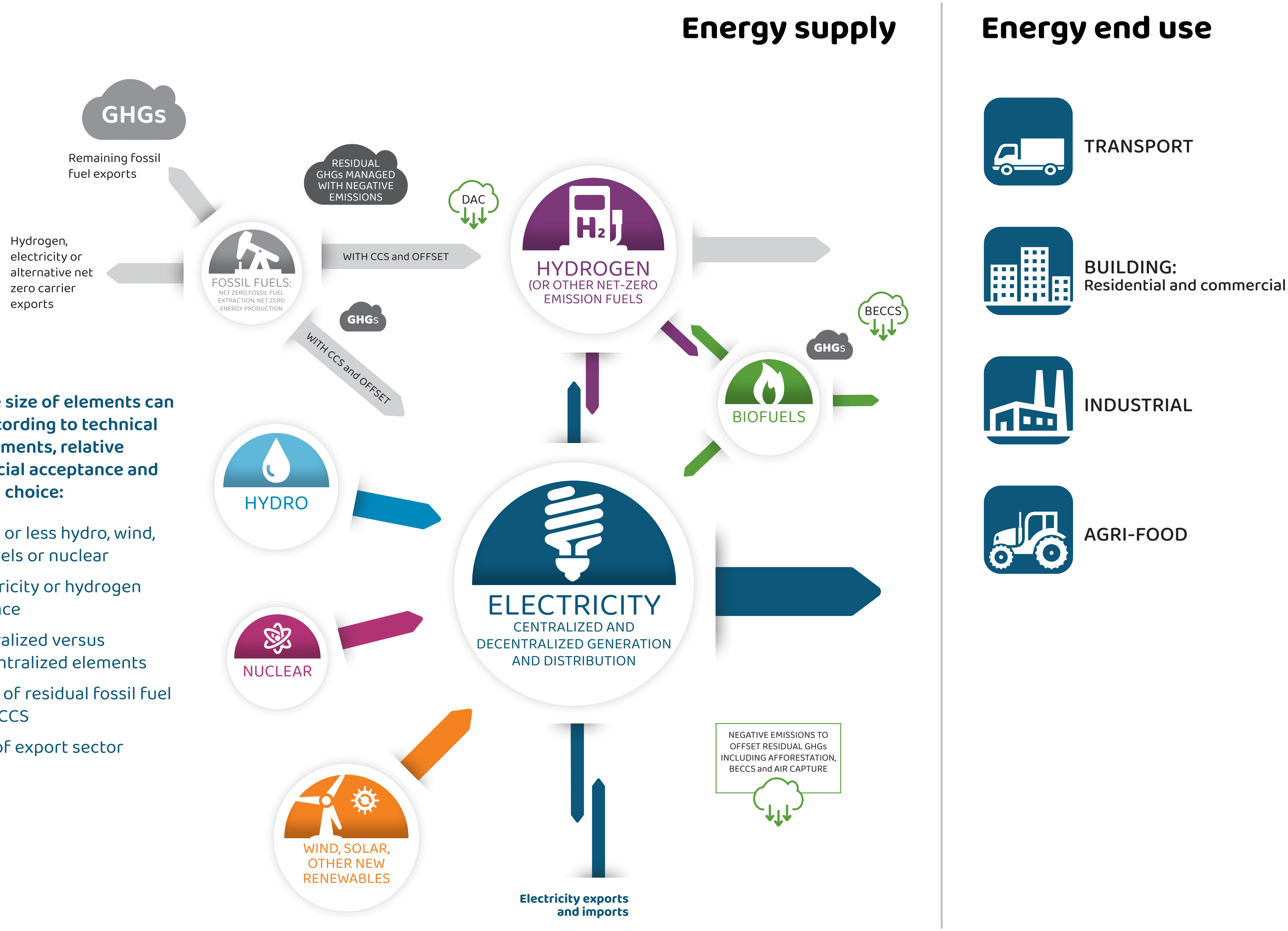


Figure 3. Schematic overview of Canada's energy system

Sources: Compiled with data from: 'Greenhouse gas emissions: Canadian environmental indicators 2020;[169] Energy Factbook 2019-2020;[213] Provincial and Territorial energy profiles – Canada.[214] For a more complete vision of energy and emission flows in Canada see: https://www.cesarnet.ca/visualization/sankey-diagrams-canadas-energy-systems

SCHEMATIC VISION OF A NET ZERO GHG EMISSIONS ENERGY SYSTEM

Energy and energy-related emissions only. Secondary flows (e.g. clean energy flows to fossil sector) and some technologically feasible processes omitted for simplicity (e.g. synthetic hydrocarbons)



Relative size of elements can vary according to technical developments, relative cost, social acceptance and political choice:

- more or less hydro, wind, biofuels or nuclear
- electricity or hydrogen balance
- centralized versus decentralized elements
- scale of residual fossil fuel with CCS
- size of export sector

Figure 4. Schematic vision of a net zero emission energy system

4. Looking beyond the energy system

Some Canadian GHG emissions are not directly related to energy use, but stem from industrial processes and products (7.5%), agriculture (8.4%) and waste (2.6%). These emissions, which are entangled with a variety of existing systems of provisioning, may be particularly challenging to address. Industrial processes include the production of iron, steel, and cement (the critical structural materials of industrial society) and the manufacture of chemicals. Industrial products include fluorinated gases used in refrigeration, air conditioning and heat pumps, as well as other industrial and commercial applications. Agricultural emissions are generated by livestock operations (from enteric emissions and manure) and cropping practices (fertilizers, agricultural soils). Landfill and waste-water treatment facilities also generate substantial GHG emissions. Moving towards net zero, system transformations must successfully address both energy and non-energy emissions, and these will be discussed together in subsequent sections of this report.[29,30,33]

Although the journey to net zero is primarily about building systems that avoid GHG emissions, it will also involve some application of 'negative emission' approaches that remove carbon dioxide from the atmosphere. This will be required to offset residual emissions which prove technically challenging or too expensive to eliminate. For example, if CCS is applied to fossil energy production and use, or to control industrial process emissions, residual emissions of perhaps 10% will have to be offset by removals. And while accidental methane releases associated with fossil energy production and usage can in principle be reduced to low levels, negative emissions approaches may be required to deal with these.

Moreover, even if all fossil energy usage stops, or novel exploitation techniques completely avoid GHG releases, negative emissions approaches may ultimately be required to draw down atmospheric GHG concentrations. Most integrated assessment models indicate these approaches will be needed in the second half of this century if the impacts of climate warming are to be kept within a manageable range.[1,2] Although some argue that these models have not accounted for more dramatic demand-led systems changes that might avoid the need for negative emissions, the longer climate action is delayed the more potential significance they acquire.[34]

A wide array of negative emission approaches has been suggested, including:

- large scale reforestation and afforestation. As trees grow, they absorb carbon dioxide and convert it into standing biomass. If the forest remains undisturbed, the carbon is locked away from the atmosphere.[35]
- increased retention of carbon in soils through changes to agricultural practices and/or the wide scale incorporation of biochar.[36,37]
- bioenergy carbon capture and storage (BECCS), where biomass energy facilities apply CCS to trap the carbon dioxide drawn down by plant growth underground.[38]
- direct air capture (DAC), where CO_2 is extracted from ambient air and sequestered underground or used as an input for industrial processes.[39]

Each approach has different potential as well as difficulties or drawbacks. For afforestation and reforestation, concerns are with the vulnerability of sequestration to fires, pest and disease attack, or human activities as well as the availability of land. The ultimate potential for organic carbon retention in soils remains uncertain, while there is still little systematic research on biochar. BECCS is currently expensive; energy is required to collect dispersed feedstocks, and there are doubts about the availability of bio-resource feedstocks without negative land use impacts. Air capture is currently very expensive and energy intensive but could ultimately be linked to synthetic hydrocarbon production. Other approaches are possible. But there are persistent doubts about the funding of removal activities, the scale at which they could be undertaken, and possible negative environmental impacts of many of them. Several recent reports provide an overview of negative emission approaches and the frameworks required for their governance.[40, 174]

5. Pathway assessments

The following sections offer an overview of possibilities for change in systems or sectors that are important for Canada's journey to a net zero GHG emission society. Each analysis reviews how things operate today, options for decarbonization, short-term barriers to change, policy priorities, and longer-term challenges. Not all sectors are treated in the same depth. Nor is every technological option examined. The focus is rather on large systems and on the most widely discussed options for change.

At the end of each section we have included tables which offer capsule assessments of potential pathway elements (particularly technologies, and some practices or approaches). In making this assessment we were guided by the following considerations:

First, the assessment is not concerned with fully elaborated pathways, which require a more elaborate analysis of sequencing change across multiple dimensions. Rather the focus is on key 'pathway elements' – technology or social innovations which can anchor transformative processes.

Second, since the purpose of a transition pathway is to link today's world with a desired future (in this case a future that meets the net zero challenge), promising pathway elements must be able to contribute to the broader system goal of net zero emissions. Either because

- they will become part of the reorganized system that meets the goal, or because
- they are a necessary intermediate step to get there (even if they may not continue in the system that achieves net zero), or because
- they can play a facilitating role (by accelerating the transition, reducing social conflict, and so on).

The fundamental criteria here is not 'can this reduce GHG emissions' (because some approaches to reducing emissions may lead no further), but rather 'can it contribute to accelerating transformation towards a net zero society'.

Third, even when a potential pathway element could in principle play one of these roles, there are questions about technological readiness, economic costs, social acceptability, appeal to critical stakeholders, and so on which may influence its potential uptake.[32,41,42]

Finally, since there are other problems with existing arrangements, and climate change is not the only social value, or even the principal consideration shaping the evolution of societal systems, it is important to consider the potential of approaches to contribute to other goals including improved services, healthier communities, enhanced resilience, and so on.[43]

In the evaluation tables we have organized these considerations under general headings which assess the extent to which options can contribute to pathways that are credible, capable, and compelling. The final column offers an overall judgement on the priority status of the approach.

BOX B

Pathway element assessment criteria

For the purposes of this assessment we use terms in the following manner:

CREDIBLE

MATURITY: the distance the option has travelled from basic concept to established solution. Has the technology moved beyond the lab? Does it benefit from decades of practical development?

ECONOMIC VIABILITY: current understanding of economic costs as compared to alternatives, both today and in the future.

SOCIAL ACCEPTABILITY: the likelihood that the option will be broadly accepted by the public. Are there groups or communities that are likely to actively oppose its deployment?

CAPABLE

FIT FOR PURPOSE: the ability of the option to perform the functions for which it is being proposed. The judgement is based on current and anticipated future performance.

NET ZERO POTENTIAL: the potential to contribute to a net zero future: (a) as part of that future, or (b) as a necessary step to arrive at net zero arrangements, or (c) as a sector change accelerant. While specific technologies and processes in a net zero society can have residual GHG emissions, system and sectoral solutions should approach zero emissions as closely as possible to avoid the necessity of securing large negative emissions elsewhere.

COMPELLING

TO CRITICAL STAKEHOLDERS: the attractiveness of the option to groups with the potential to advance development and implementation. These could be business, societal, Indigenous or government stakeholders. An option without active proponents will have difficulty moving forward. 'Critical stakeholders' may or may not include current sector incumbents as change may be driven by external innovators.

RELATED COSTS AND BENEFITS: Non-GHG societal gains or losses associated with deployment of this option, that may encourage or discourage implementation, and may drive system transformation.

ECONOMIC DEVELOPMENT OPPORTUNITIES: economic opportunities for Canada in a decarbonizing world. Can the option generate jobs, markets, business opportunities and promote Canada's future comparative advantage?

PRIORITY APPROACH

The extent to which the option should command the attention of decision makers today. This draws on the evaluation of the eight categories cited above, focusing on the strategic potential to accelerate system movement towards net zero. What 'priority status' currently entails for policy and investment depends on the option's state of development, the phase of the sector transition, and the broader economic and political context. In some cases, action should focus on accelerating immediate deployment, in others further research, trials or experiments might be required today to prepare for larger scale deployment in the future.

5.1 **Sector**: Power (Electricity)

Function	Provides lighting, heating, cooling, mobility and powers motors, other machinery and devices that underpin modern society; enables industrial processes
GHG emissions	9% of Canadian GHG emissions
Options for decarbonization	Replace fossil generation with non-emitting sources; deploy additional low carbon generation (centralized and distributed), and transmission and support technologies, to meet the increased role of electricity in providing energy services; manage demand to limit required generation capacity additions and energy requirements.
Stage of transition	Diffusion
Nature of the problem today	Some provinces still heavily dependent on fossil energy; ageing infrastructure; concerns over rising costs; tradition of provincial autarky
Other systemic issues	Energy reliability/security; electricity costs and efficiency losses; centralized versus distributed control
Opportunities and concerns	Reduction in air pollution; clean electricity exports; economic opportunities
Priorities for action	Phase out of coal; interprovincial transmission ties between carbon-intensive and clean provincial grids; support for renewables deployment; enhancement of grid infrastructure; measures to manage electricity demand
Longer-term issues	Increased electricity supply and storage capabilities to reliably electrify transportation, buildings, and industry; integrating a large proportion of intermittent/variable renewables (wind, solar) on electricity grids; where appropriate accommodating more distributed generation
Indicators of progress	Per cent electricity demand supplied by non emitting sources; proportion of energy end-use provided by electricity

The electricity system provides power for lighting, heating and cooling, mobility, and the operation of machinery and electronic devices. Its energy services are vital to the health and welfare of Canadians, to economic productivity and growth. In 2018 Canada generated 647.7 terawatt-hours of electricity (about 3% of the world total) and the country was the sixth largest global producer.[44] The sector employs approximately 89,000 people and contributes $34 billion to Canada's GDP.[45] Net electricity exports to the United states in 2018 were about 7% of Canadian production.

Canada's electricity sector is currently among the cleanest in the world, with more than 80% of power coming from emission free sources (60% hydro, 5% wind and 15% nuclear). Most of the remainder comes from coal (8%) and natural gas (9%) (**Figure 5**).[44] The generation mix varies widely from province to province (see **Figure 6**). Provinces can today be divided into three groups: hydro provinces with more than 90% of generation from hydro (Quebec 95%, Manitoba

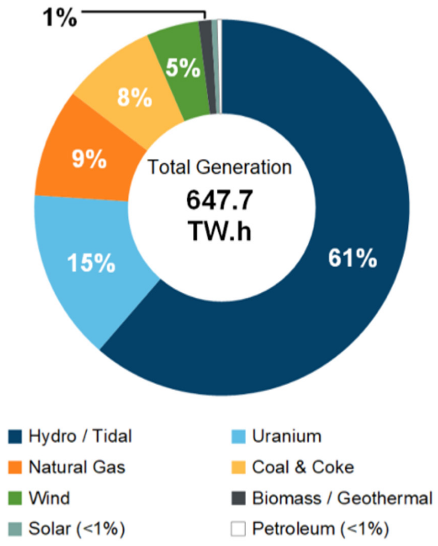


Figure 5. Canada, electricity generation by fuel type (2018)

Source: Canadian Energy Regulator 2020

97%, Newfoundland 95%, and British Columbia 91%); fossil provinces where three quarters or more of power is derived from fossil fuels (Alberta 92%, Saskatchewan 85%, and Nova Scotia 76%); and mixed-supply provinces (Ontario with 60% nuclear, 26% hydro, and 9% wind/solar; and New Brunswick with 39% nuclear, 21% hydro and 10% wind/other renewables). The remaining jurisdictions of PEI, the Yukon and North West Territories, and Nunavut together account for less than 0.5% of Canadian production.

The division of powers under Canada's constitution means that electricity systems are essentially under provincial control, although the federal government has regulatory responsibility for the nuclear industry, electricity exports, national and international pollutants, and inter-provincial transmission.[46] Provinces have always viewed electricity policy as a critical lever for economic development, and jealously guard control over generation and transmission. North/South grid interties with US markets are more developed that East/West interprovincial grid connections.[32] The eight mainland Canadian provinces are integrated into the grid balancing areas of the North American Electric Reliability Corporation (NERC).

In most provinces, electrical utilities are vertically integrated Crown corporations. Deregulated wholesale electricity markets exist in Alberta and to some extent in Ontario. Industry accounts for the largest share of domestic consumption (41%), followed by residential buildings (33%), the commercial and institutional sectors (23%), agriculture (2%), and transport (0.3%). Again, there is variation across provinces (**Figure 7**).

Canadian electricity prices are among the lowest in the OECD but differ from province to province. There are arguments over how best to compare rates (at what level of monthly consumption, before or after taxes, and so on) but the basic pattern of variation is captured in **Figure 8**. Industrial bulk users receive significant discounts and hydro provinces typically have the cheapest rates.[184]

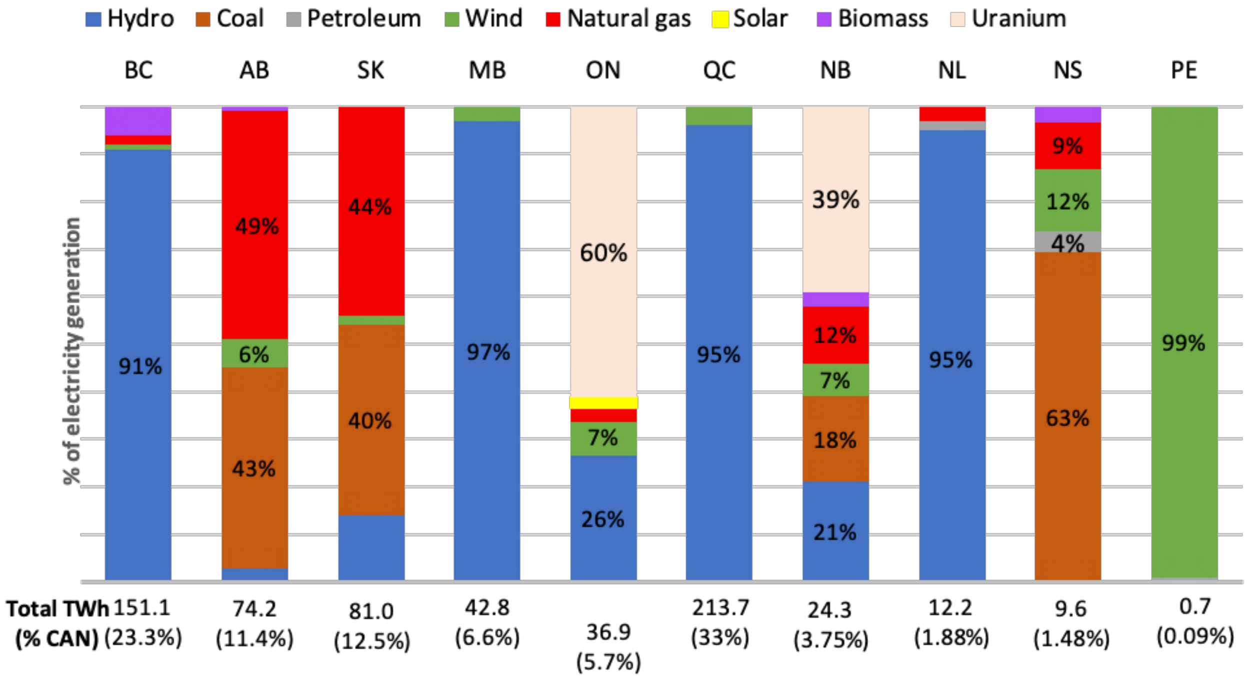


Figure 6. Electricity generation by fuel type in Canadian provinces, 2018

Source: Canada Energy Regulator (CER), 2019

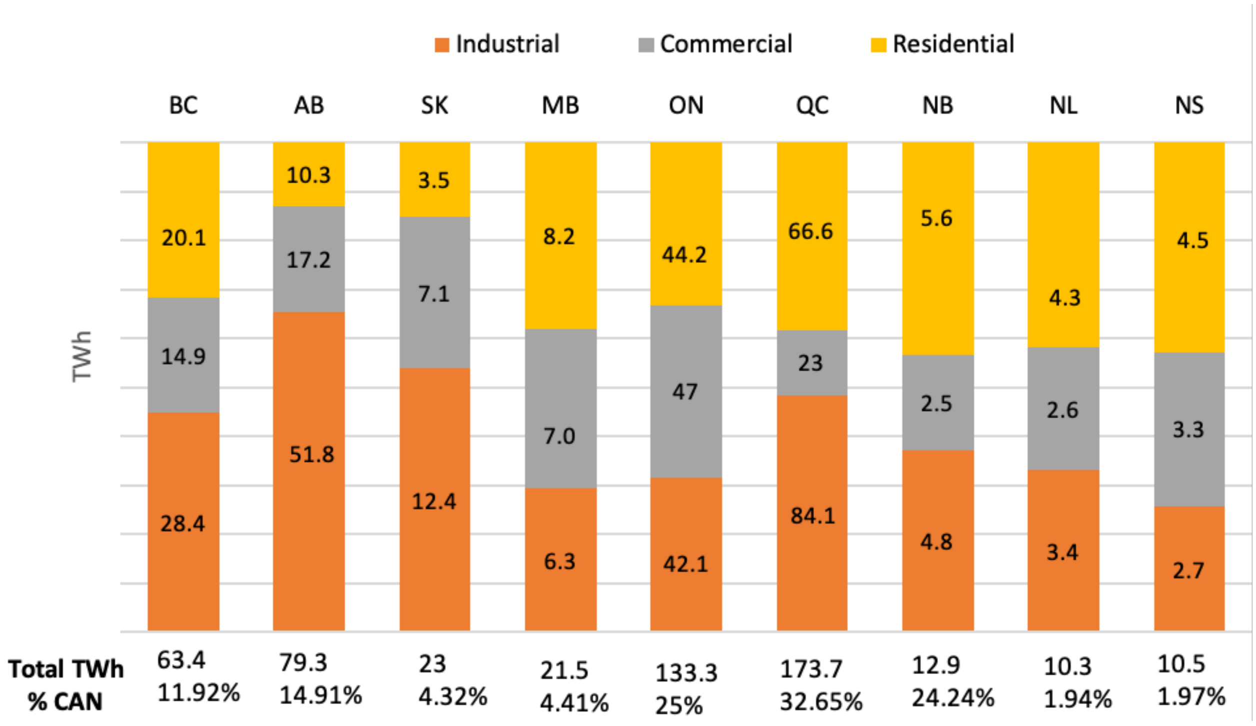


Figure 7. Final electricity consumption by major sectors in Canadian provinces, 2018

SOURCE: CANADA ENERGY REGULATOR (CER), 2019

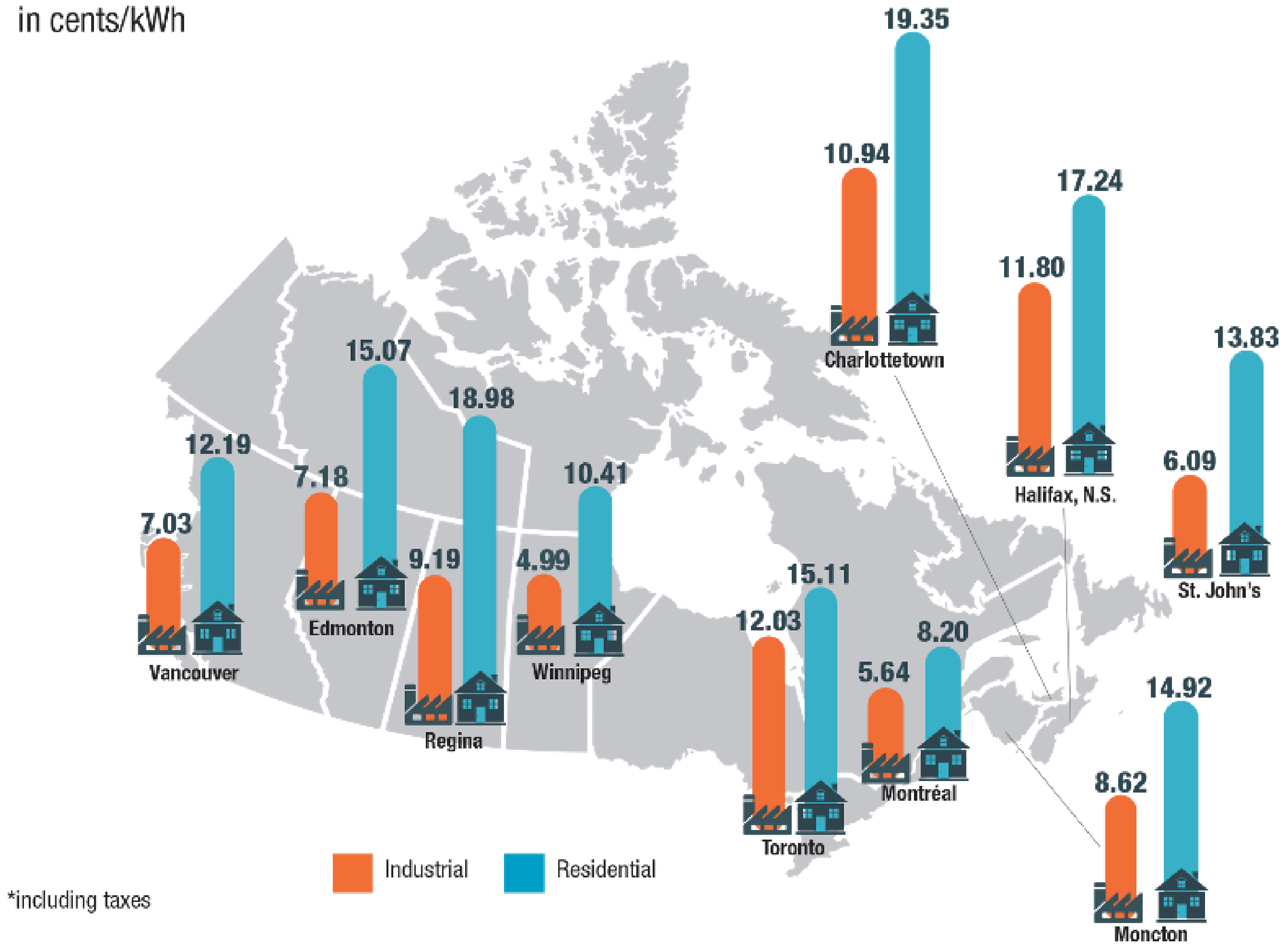


Figure 8. Average large industrial and residential electricity prices, April 2018

Source: NRCan, 2020. Electricity facts.

NATURE OF THE PROBLEM

Electricity systems have a pivotal role to play in decarbonization, as power can displace fossil fuel end-uses in transport, buildings and industry. At a global scale, the shift to low carbon electricity is well underway, with dramatic falls in the price of wind and solar generation encouraging ever wider deployment (see **Figure 9**).[47] In this context, Canada enjoys three distinct advantages. First, our electricity supply is already substantially decarbonized.[44] Second, we have generous renewable resource endowments (including wind and solar, but also tidal and geothermal), often located in areas where fossil energy dependence is highest today. And third, our abundant legacy hydro (the second largest installed capacity in the world) can provide an energy storage solution to help balance grids and facilitate the large-scale integration of intermittent renewables.[48] Canada's ready access to low carbon energy, and potential to rapidly complete the decarbonization of electric supply, is a competitive advantage to attract businesses seeking cheap net-zero emission power (for battery or EV manufacture, minerals processing, etc.).

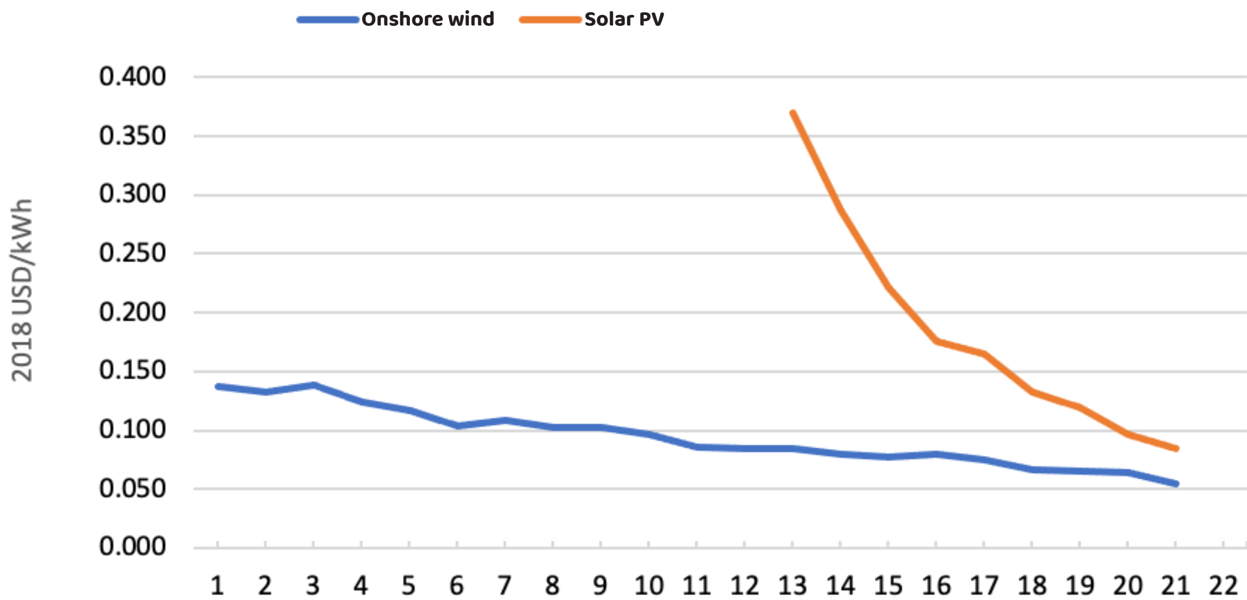


Figure 9. Global weighted average of levelized cost for onshore wind and solar PV, 1998-2018.

Source: IRENA, 2018

Nevertheless, the current split between low and high carbon provincial electricity systems poses serious challenges. The financial and political effort required to transform the fossil-dependent systems will be significant, requiring the construction of new generating capacity, retirement of fossil assets before their anticipated lifetime, and movement away from coal or gas produced within the province. Most models suggest the cost of fully decarbonizing Canadian electricity systems could be lowered by closer inter-provincial coordination (with new and expanded interties between hydro-rich provinces and their neighbors). While this flows against the tradition of provincial independence,[32,49] the federal government appears interested in encouraging such linkages.[185,186,187]

Other current challenges relate to public sensitivity over rising electricity costs, aging electricity infrastructure, electricity rate structures not aligned with the shift to net zero, and potential opposition to large scale energy projects (generating facilities, transmission lines). Over the past decade average electricity costs in Canada have increased more rapidly than inflation.[50] The largest increase has been in Ontario, where prices rose by two thirds between 2007 and 2016. Although household energy spending averages only 2.6% of domestic budgets, increases hit lower-income families particularly hard. And electricity price rises are always politically salient. Drivers of this rise in Ontario included the costs of moving off coal, refurbishment of aging nuclear plants, grid modernization, and decades of artificially suppressed prices and lack of investment. Although price rises in Alberta have been modest (because of exceptionally low natural gas prices) managing cost pressures will be an important consideration in advancing electricity decarbonization. Much of Canada's electricity infrastructure dates from the post-war period, requiring projected investments of nearly $1.7 trillion by 2050.[45] Public opposition to large energy infrastructure projects is not confined to pipelines, and resistance to the construction of generations assets (power plants, wind or solar developments) and transmission could raise costs, introduce delays or forestall potential projects.

NET-ZERO PATHWAYS

Moving Canada's electricity systems towards net-zero involves two inter-related tasks: decarbonizing the existing electricity supply and expanding electricity systems so they can power sectors currently dependent on end-use fossil fuels. Both involve (a) building net-zero electricity generation; (b) adjusting electricity grids to make them more flexible, smart, and resilient; and (c) managing demand and encouraging energy efficiency to limit the need for additional generation. This will require a combination of centralized and decentralized energy solutions. Ultimately a net zero electricity system may be integrated more closely with other parts of the energy system: for example, with hydrogen produced through electrolysis (or from fossil resources with CCS), which can serve as an electricity storage medium and meet demand in other sectors.

The first challenge – decarbonizing existing electricity supply — is most acute in fossil dominated provinces (Alberta, Saskatchewan, Nova Scotia), but there is work to be done in New Brunswick and Ontario. The second challenge – gradually expanding capacity to meet increased demand — faces all provinces, even those like Quebec, Ontario and Newfoundland which currently have power surpluses.

Modeling suggests that electricity demand might double or more by mid-century in a decarbonized economy.[172,189] Increasing power production and distribution on this scale over coming decades represents an enormous task – especially in a context where energy projects today can stir substantial public opposition.

1. Low carbon generation: There are many ways to make relatively inexpensive net zero emission electricity, but each approach has costs as well as benefits.[135] Hydro forms the backbone of most Canadian electricity systems, providing cheap and reliable legacy power. But sites close to demand centers have already been exploited, environmental impacts are substantial, capital costs and cost overruns (such as those at Muskrat Falls in Labrador and 'Site C' in British Columbia) are a significant concern, and there has been opposition from Indigenous communities. It is generally assumed that for now there is limited potential for further large-scale development. Canada has tremendous wind resources and prices have fallen so much that wind often represents the cheapest incremental addition to grids. Yet wind is intermittent in the short term and its energy output varies by season, so a backup and/or storage is required for when it does not blow. In some Canadian jurisdictions there is public opposition to further wind development. Offshore wind is where significant global investment is going, and may make sense for Canada's coastal provinces, including Ontario on the Great Lakes. The costs of solar photovoltaic continue to fall. Canada has substantial solar potential, but again daily and seasonal variability is an issue. Other renewables (tidal, wave, geothermal) have promise, but remain further from market and are limited geographically. Nuclear provides GHG emission-free, reliable, baseload power in Ontario and New Brunswick. Disadvantages include high capital costs, inflexibility (plants cannot be ramped up or down to follow intermittent renewables), security, waste disposal, and substantial public opposition to new build.[51] Small modular reactors (SMRs) are a possibility for the future, but the technology remains to be proven and large-scale deployment may be several decades away.[52] Fossil combustion with CCS (with offsets to handle residual emissions) is possible. But coal with CCS appears expensive compared to renewables, and emits many hazardous pollutants.[53,54] Gas with CCS could serve to back up variable renewables.

For now, wind presents the cost point for other technologies to beat, but solar continues to decline rapidly. Least cost models of decarbonization in Canada currently suggest massive wind power additions even in hydro provinces.[49] Energy storage is an important consideration in building low carbon generation capacity, and electricity/hydrogen linkages (where hydrogen serves as storage and a complementary energy carrier) could increase the overall flexibility of the energy system. But it is not possible today to anticipate exactly how low carbon supply will develop. Choices in each province will be influenced by specific system attributes (sunk investments), capacities and decisions of neighboring jurisdictions, the evolution of technologies and comparative costs, public attitudes, market design. and political calculus.

2. Resilient and flexible grids will be essential to deliver decarbonized supply and expanded end-use electrification.[134] Grids will accommodate variable and more widely distributed generation (eg wind and solar), support larger power flows (delivering more energy to end users), connect over longer distances (to balance loads), service more diverse end uses (electric vehicle charging) and allow more sophisticated demand management (to reduce peak usage). Investment in interprovincial and/or international interties, storage (battery, pumped hydro, compressed air, hydrogen, etc.), enhanced communications and control systems (smart grids) will be important. So too will be adjustments to market design and regulatory mandates to accelerate needed investment.[55,56,57,188,189]

3. Energy efficiency and demand management can reduce the generation and transmission capacity required to deliver expanded energy services. Efficiencies can be sought on the supply side to enhance generator performance and reduce transmission and distribution losses, but more significantly on the demand side through improvements in technologies providing energy services (for example, space conditioning for buildings). Demand management programs that displace use over time (to off peak hours) or allow customer loads to be curtailed during extreme weather events or other crises can reduce the need for peaking plants and transmission upgrades and contain costs.[58] These programs can involve new technologies, program designs, and institutions (energy efficiency utilities, 'behind the meter' energy management companies). Potential efficiency gains and demand reduction should generally be considered before investment in new generation and transmission (which always adds costs and environmental consequences).

An important but open question for long term decarbonization is the extent to which the supply and management of power is centralized or decentralized. Very different visions of net zero energy systems co-exist today. On the one hand, there are highly centralized designs where power is produced in areas with maximal renewable resources (for example, deserts for solar or off-shore for wind) and then moved across continents to load centers.[59] And on the other, highly decentralized models where electricity is produced and consumed locally (perhaps involving microgrids, or tens of millions of 'prosumers' –producing and consuming their own power), with traditional grids serving back up and balancing functions.[60] Choices that would generate one or another alternative are political as well as related to economics, technologies and resource availability. Yet there are many reasons for believing that real-world systems will involve a complex and nuanced mix of centralized and decentralized elements. There are advantages to local power production (at the building or community level) – reducing the need for large-scale projects, avoiding transmission losses and grid congestion, and promoting increased local control and resilience. And yet economies of scale, and linking regions with different resources and load profiles, are also attractive. So, a pragmatic approach makes sense, that combines both centralized and decentralized elements to optimize overall benefits as net zero emission power systems are built out.

PROVINCIAL INITIATIVES

Critical decisions about the future of Canadian electricity systems will be made at the provincial level, but the federal government can do much to support greater coordination and encourage low carbon technologies and infrastructure. For example, through co-financing important initiatives, implementing carbon pricing, and developing regulatory standards that phase out unmitigated fossil-fired generation (as has already been done with coal).

In making choices, the provinces face distinct geographic circumstances and resource endowments, legacy generation and transmission infrastructure, regulatory structures, and political economic realities. Three jurisdictions, Ontario, Alberta, and British Columbia serve to illustrate the issues confronting electricity systems in Canada.

Ontario has a hybrid market design with substantial public ownership, complex lines of authority, and 60 local distribution companies. Electricity policy is highly politicized, with recent arguments about the roll out of renewables and the rise in energy prices. After the coal phase out, Ontario has a comparatively clean grid, dominated by nuclear power. While nuclear units are taken out of service for refurbishment over the coming decade increased emissions from natural gas plants are likely. In the longer term, the province faces a major choice about whether to retire the nuclear fleet or reinvest in new facilities. The stakes for the province and Canada's nuclear industry are high. Either way, the province will eventually require additional wind and solar capacity. Enhanced transmission interties with Quebec, and aggressive energy efficiency programs, could keep costs down and slow the speed at which new generation capacity must be built out.[61]

Alberta has a substantially deregulated power market. It faces the greatest challenge to grid decarbonization in Canada. Getting off coal as soon as practical makes sense because of air quality as well as GHG emission reduction. Careful assessment of pathways to net zero should be conducted rather than simply replacing coal-fired plants with gas-fired generation, which would later have to be coupled with CCS or phased out before its planned end-of-life. A turn toward wind and solar, coupled with investments in grid interties with British Columbia, and the development of geothermal (especially closed loop) as well as hydrogen pathways make sense. Major questions remain about electrification of oil sands operations and the implications for electricity supply.

In British Columbia, a vertically integrated Crown corporation (BC Hydro) serves more than 90% of customers. Electricity demand is forecast to grow strongly over coming decades. Further hydro development is politically contentious, as is the development of wind and run-of-the-river projects by independent power producers under contract to BC Hydro. The 'site C' project currently under construction on the Peace River attracted significant opposition from Indigenous communities and environmental groups. But the province has enormous wind potential. Key areas of focus going forward include efficiency and demand management, continuing modernization and upgrades of transmission and existing hydro facilities, and incremental additions of renewables especially wind. A critical issue remains British Columbia's ambition to become a major LNG exporter and a commitment to electrify future liquefaction, as well as associated upstream natural gas production infrastructure (compressors, pumps, etc.), with clean electricity, with obvious implications for electricity supply.[62]

In all cases, provincial politics play a significant role in the structure and design of electricity markets. If Canada is to meet long term decarbonization goals in a cost-effective manner there will need to be a concerted effort to break through parochial electricity market rules that prevent access and flexibility, and to enhance the potential for inter-jurisdictional coordination.

SHORT- AND LONG-TERM PRIORITIES

Priorities for action differ by province. For the fossil-dependent jurisdictions, increasing energy efficiency, investing in renewable generation, building interties with neighboring hydro provinces, and phasing out coal are the most urgent tasks. Federal regulations set 2030 as the deadline to end unmitigated coal generation, but decommissioning plants earlier will lower carbon intensity and secure immediate air quality gains. Simply replacing coal plants with new gas plants, should be avoided. With the continuing fall in wind and solar costs it makes more sense to build up renewable resources steadily, particularly since the fossil-based systems are well buffered with gas. As it is quite possible that emission abatement targets will be further tightened over coming decades, even 'CCS ready' plants will pose a risk, so a straight switch to renewables is more prudent to prevent the further stranding of fossil assets.

For the hydro rich provinces, incremental build out of wind or solar can be timed to provide additional supply as needed. Large hydro facilities provide opportunities for storage to meet peak demand and balance intermittent resources. Active exploration of interties with neighboring provinces and/or US states offers the possibility of more flexible and resilient grids, and additional revenues or reduced power costs, through power transactions. At some point all jurisdictions should:

- Put greater effort into long-term power system planning, targeting net zero GHG emissions by mid-century. This involves exploring generation scenarios that minimize GHG emissions from supply options and grid improvements, in the context of demand scenarios that include the electrification of end uses, modeling potential system configurations two, three and four decades out. Scenarios should focus on system transformation (including radical demand shifts), and not just incremental market-induced adjustments, and explore implications of on-going radical cost reductions in clean technologies, demand response and efficiency approaches, as well as collaboration with other jurisdictions.

- Introduce regulatory and/or market reforms to make system decarbonization and expansion a central preoccupation of all system participants. Most provincial electricity markets are designed to limit access, limit flexible market participation, limit imports and exports, and facilitate central control. This historic approach to electricity system planning needs to shift to one of open access, flexibility, policy certainty, competition, and opportunities for market participants to operate in demand response, efficiency, supply, storage, and financing. Regulatory bodies must create regulated return models based on incentives to achieve net zero and eliminate sales and capital expenditure-based rate of return structures.
- Ramp up incremental investments in transmission infrastructure (modernization, smart grids, distribution, renewables access, etc.) and storage, to build flexible and resilient grids that can be adapted to shifting demand, and technological innovation.
- Involve electricity companies and regulators more directly in electrification of GHG emitting energy end-uses (such as transportation, space heating and cooling buildings, and industrial processes) to actively steer the way new loads are integrated into the grid (for example the tens of millions of electric vehicles that will require charging).
- Support indigenous power initiatives across the system, including northern and off-grid community supply projects, building efficiency, and building replacement, geothermal, skills training, and Indigenous-led finance mechanisms.
- Accelerate development and investment in new technologies, including geothermal, small modular reactors, hydrogen linkages, energy storage and smart grid technologies.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Power** (Electricity)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
New generation									
Hydro reservoir	Mature	Closest sites already exploited. Significant capital costs for large dams and transmission linkages. Smaller projects more viable.	There can be substantial opposition from environment and Indigenous groups. Smaller projects with indigenous stake more acceptable	Yes. Provides reliable bulk power and dispatchable power to support integration of variable renewables (wind, solar)	Yes. Emissions from reservoir flooding, but these can be mitigated and decline over time.	Especially when there are local and Indigenous proponents.	Can balance intermittent renewables. Significant environmental costs.	Yes. Especially today in remote and Indigenous communities.	Medium. Yes, for smaller scale projects. Possibly over longer term for larger projects.
Hydro run of the river	Mature	Can be competitive depending on conditions	There can be opposition from environment and Indigenous groups. Less significant than for reservoir projects. Smaller projects with Indigenous stake more acceptable	Yes. Provides reliable power.	Yes.	Especially when there are local and indigenous proponents.	Modest environmental costs but less significant than reservoirs	Especially today in remote and Indigenous communities	Yes, for smaller scale projects. Possibly for larger projects depending on context.
Wind	Mature	Highly cost competitive. Often lowest incremental addition. But dealing with variability may add system costs	Considerable opposition in some areas. Softened with forms of community participation. Offshore often more acceptable.	Yes, but variable power. Large offshore projects very capable. Easily dispatchable. Weather forecasting improving.	Yes. Likely to be a fundamental pillar of net zero electricity systems. For high penetration needs storage, regional integration, or other ways to manage variability.	Increasingly to system operators because of falling costs and growing experience	No air pollution. Some environmental issues (birds, bats, visual)	Yes. Jobs and development opportunities. Community ownership in projects possible. Revenue for farms.	High Likely part of net zero emission world
Utility scale solar PV	Maturing	Increasingly cost competitive, especially in areas with high solar irradiance.	Generally high. But some opposition in rural areas as part of a general anti-renewable backlash.	Yes, but variable. Less effective in cloudy and low temperature environments with heavy snow cover. Weather forecasting improving	Yes. Likely to be a fundamental pillar of net zero electricity systems. For high penetration needs storage or other ways to manage intermittency Assuming net zero lifecycle of panels (manufacture, disposal)	Increasingly to system operators because of falling costs and growing experience	No air pollution End of life panel recycling and material recovery immature	Yes, through community ownership. Some jobs and development opportunities.	Medium to high Likely part of net zero emission world
Small scale and residential PV	Mature	Typically requires subsidies in Canada today	No problems	Yes, but varies with geography. Requires storage and/or grid linkage	Yes. Assuming net zero lifecycle of panels (manufacture, disposal)	Interest from homeowners to reduce utility bills, be independent	Can reduce grid load, useful at peak, highly viable in remote operations with battery storage. Added complexity for grid management. End of life panel recycling and material recovery immature	Yes, for installers, some equipment manufacturers (inverters, racks, control systems). Additional revenue stream for farms, small businesses.	Medium to high. Can be part of low carbon world.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Power** (Electricity)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Building integrated PV	Still emerging for roofs, facades, windows. Mainly at demonstration stage	Still more expensive than comparable building elements	No problem	Yes, but power flows modest compared to current energy requirement of most buildings	Yes. Assuming net zero lifecycle of elements	Interest from architects, designers of net-zero buildings	Reduces demand for power from grid. Helpful in peak periods, or with congested grids	Yes, for companies developing new products.	Medium. Can be part of low carbon world.
Biomass combustion	Mature	Low cost	Potential local opposition to plant siting (trucks and air pollution) and environmental opposition to biomass extraction	Yes. Only viable for smaller scale operations near active biomass extraction due to cost of moving feedstocks	In principle, if biomass is grown in a net zero way. Not practical as a general solution because of limited fuel supply. Competing uses for land and biodiversitypressures. Could be used with CCS to generate negative emissions	For industries with waste biomass.	Can facilitate intermittent renewables. Useful for industrial applications with waste (forest products). Produces air pollution	Local opportunities connected to existing biomass extraction	Low to medium except in specific contexts. Can be part of low carbon world.
Geothermal	Demonstration scale in Canadian context.	Not cost competitive today	No problem today. For some technologies local concern over fracking and seismic activity	Yes, in principle. Continuous baseload power	Yes. Applicable in certain regions. Closed loop systems much preferable	No strong constituency yet, but emerging	No air pollution Some local environmental concerns	Potential development opportunities in Alberta.	High priority for closed loop demonstration and investment
Nuclear conventional	Mature	Relatively expensive. No new builds in Canada for nearly 30 years. Consistent cost overruns.	Doubtful. Strong legacy public opposition to new build nuclear.	Yes, reliable bulk baseload power. But no new conventional reactor designs being developed in Canada.	Yes. Provided lifecycle of mining to decommissioning also decarbonized	Support from existing industry and value chain	No air pollution. Could be source for hydrogen production. Multiple issues: long term waste storage, decommissioning costs, risk of accident, security	Yes. Depending which parts of value chain were in Canada. Nuclear industry currently supports many jobs.	Low today. Highly unlikely given that the industry has moved to SMRs.
Nuclear (SMRs)	Research and development stage	Unclear, too early in development to determine	Strong legacy of public opposition to new build nuclear, offset by nuclear host communities often very supportive of new investment.	If development is successful could provide reliable bulk baseload power. Early markets in remote communities, mine sites, industrial heat etc.	Yes. Assuming decarbonization of fuel production and reactor fabrication.	Strong support from those involved in existing nuclear supply chain	No air pollution. Could be source for hydrogen production. Multiple issues: long term waste storage, risk of accident, security, decommissioning costs.	Yes. Nuclear industry is a large employer. Possible export markets if a successful design is developed. Doubts about Canada's ability to scale up for export	Medium. R&D for now. Too early to identify final potential
Coal with CCS	At large scale demonstration stage	High capital costs. Currently requires significant state support	No organized opposition to CCS today. Some worries about storage permanence. Some opposition to coal and anything that enables its persistence	Yes. Some energy penalty (need to burn more coal for energy for CCS).	In principal yes, with offsets for uncaptured lifecycle emissions (combustion, mining, transport)	Little interest in Canada among coal suppliers and generators.	Air pollution and environmental impacts of coal mining.	Limited. Amine technologies owned by others.	Not a priority. Could be required in some countries. Not needed in Canada because of abundant alternative resources.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Power** (Electricity)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Gas with CCS	At large scale demonstration stage	High capital costs. Currently requires significant state support. Could ultimately be cost competitive with other dispatchable power	No organized opposition to CCS today. Some worries about storage permanence.	Yes. Some energy penalty.	Yes in principle, with offsets for uncaptured lifecycle emissions (combustion, extraction, transport)	Some interest among Canadian gas suppliers and generators.	Can use existing gas infrastructure. Can serve as backup for intermittent renewables. Less storage space required than for coal	Limited unless R&D breakthroughs lead to Canadian technologies	Medium for now. May be used (with offsets) as back up for renewables
Grid and system upgrades									
Inter provincial interties	Mature	Yes. Economics depend on particular project	Active public opposition along route whenever new transmission is proposed	Yes. High voltage DC lines especially useful	Yes. Enabling technology for further deployment of renewables and cost containment	Should be support from exporting jurisdictions. Fraught with political difficulties because of provincial politics	Lowers decarbonization costs. Enhance grid resilience. Revenues to net exporting provinces. Environmental impacts.	Limited: already mature industry	High. Can be part of net zero future and accelerate its arrival
Canada / US interties	Mature	Yes. Economics depend on particular project	Active public opposition along route whenever new transmission is proposed	Yes. High voltage DC lines especially useful. Underwater DC cables where possible	Yes. Enabling technology for further deployment of renewables and cost containment	Many actors see potential gains but building supportive political coalitions on both sides of the border is difficult. Political risks. For some provinces there are decisions about prioritizing interprovincial and US links	Lowers decarbonization costs. Can facilitate decarbonization especially for US side. Enhance grid resilience. Revenues to net exporting provinces. Environmental impacts	Limited: already mature industry	Yes. Can be part of net zero future
Grid improvement	Various levels of development from established to emerging	Various cost structures	No problems with most options as they occur out of sight. Increased power lines may spark opposition	Yes, different upgrades perform different functions	Can contribute to net zero by containing costs, raising efficiency, reliability, resilience Adding more distributed generation sources.	Power companies enthusiastic but worried by who pays	Low electricity costs; more reliable supply, improved power quality, enhanced services	Some local businesses; equipment suppliers	Medium high Necessary facilitating investment
Storage	Various levels of development Pumped hydro: high. Batteries still developing. Hydrogen not yet practical. EV batteries as integrated storage exploratory	Generally expensive. Today only cost competitive in specific contexts: peak shaving, arbitrage, remote locations	Will depend on specific technology.	Yes. But long-term storage of bulk electricity only possible in hydro reservoirs. Pumped storage when terrain allows and used economically. Battery storage dependent on tech breakthroughs.	Important technology for moving to net zero to facilitate deep intermittent renewable penetration.	Seen by most stakeholders as a positive in terms of facilitating intermittent renewables.	Considerable economic benefit to electricity system balancing, reliability, dispatchability.	Future economic opportunities depend on technologies and context.	Medium high needed to facilitate renewables

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Power** (Electricity)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Demand management	Many approaches well tested	Often cheaper than adding generation and/or transmission	High. But care must be taken to design and communicate programs	Yes	Yes an essential part of net zero pathways	Companies that design and administer these programs and large electricity users who benefit.	Reduces grid peak loads, lowers energy costs, reduces environmental burdens (through avoided generation).	Limited, although can assist profitability of large end users	High to reduce need for new generation
Energy efficiency	Many approaches well tested	Often cheaper than adding generation and/or transmission	High	Yes	Yes, an essential part of net zero pathways	There are advocates for energy efficiency but often potential is overlooked	Reduces grid peak loads, lowers energy costs, reduces environmental burdens (through avoided generation). Saves money for customers and power providers.	Yes, has largest job multiplier of any energy sector investment, especially in end use sectors such as building retrofits.	High to reduce need for new generation

5.2 **Sector**: Transportation

Extensive movement of people and goods is a defining feature of modern society. Whether one moves by car, truck, train, ship or air, transport is today almost entirely dependent on fossil fuels (gasoline, diesel, fuel oil and kerosene). Decarbonizing transportation, currently Canada's second largest source of GHG emissions, will require transformational change in technologies and practices across all modes. Here, however, the discussion focuses on two critical elements of the road transport sector: light duty vehicles and heavy trucks.

Road transport lies at the core of the current system. It also generates the bulk of transport related GHG emissions, which have risen by more than 80% over the past 30 years (see **Figure 10**).[33,63]

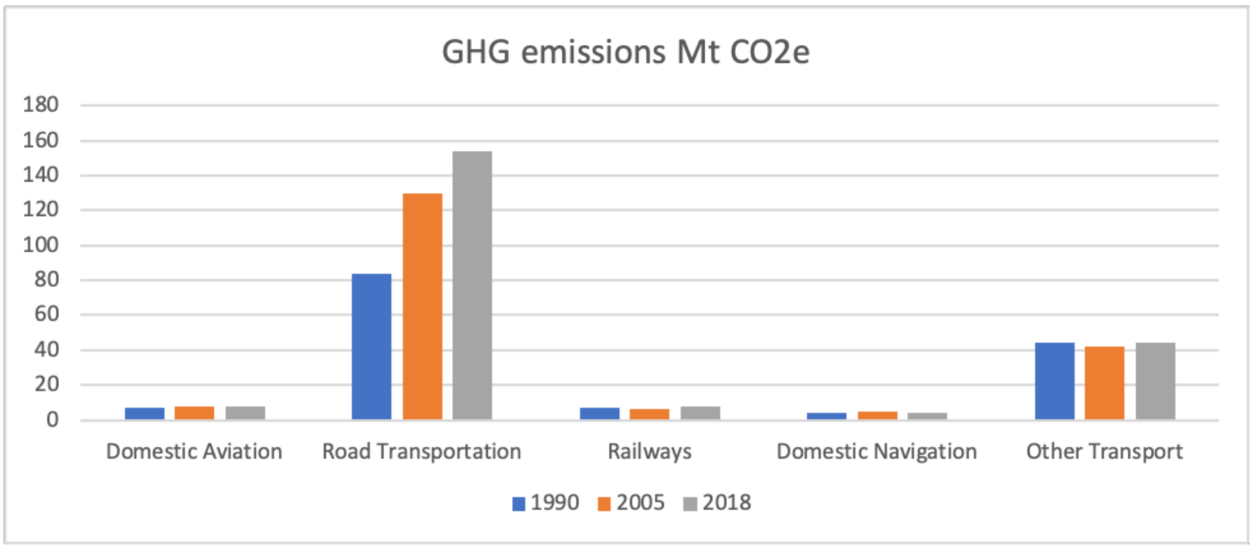


Figure 10. GHG emissions from transport (Canada), selected years.

Source: National Inventory Report 1990–2018: Greenhouse Gas Sources and Sinks in Canada, p. 36

In 2016, Canadians spent on average 70 minutes a day travelling. And those trips were made principally in light duty vehicles (see **Figures 11**). Although most Canadian cities have some form of mass transit, 80% of commuters get to work by car.[64] For three quarters of a century our cities have co-evolved with the private automobile. Land use patterns and population densities, as well as expectations about housing and lifestyle, pose significant difficulties for traditional public transit. Problems associated with the current personal mobility system include costs of car ownership, low-quality urban spaces, congestion, traffic accidents, noise, and air pollution.[65–67] Yet a series of innovations are beginning to disrupt the established internal combustion engine/private automobile based transport system, including alternative power trains (electric, hybrid electric and fuel cell vehicles), new business models (Uber, Lyft, etc.), changing attitudes towards car ownership, and the prospect of connected and autonomous vehicles.[68–71]

Mode	2017
Bus	58,987
Cars	288,392
Passenger Truck	254,934
Air-passenger	211,067
Rail-passenger	1,529

Figure 11-A. Canada passenger travel in 2017 in passenger-kilometres (millions)[196]

Main mode of commuting	2016
Car, truck, van - as a driver	11,748,095
Car, truck, van - as a passenger	868,920
Public transit	1,968,215
Walked	877,985
Bicycle	222,130
Other method	193,595

Figure 11-B. Main mode of commuting for the employed labour force aged 15 years and over in private households with a usual place of work or no fixed workplace address[197]

Approaches to transform the system and lower GHG emissions from passenger vehicles include:

- Avoiding travel through 'teleworking'. Enabled by digital technologies, this option may finally have been given a decisive push by the Covid-19 crisis as employers and employees have realized daily travel to a central workplace may not be essential.[72]
- A switch to active transportation (walking and biking) that also promotes individual health, but which requires investment in alternative infrastructure (bike lanes, bike parking) and is constrained by the current urban form and (in much of Canada) by harsh winters.[73]
- Expanding and decarbonizing mass transit.[199] This would also ease road congestion, and requires infrastructure build-out, and attitudinal shifts.[74]
- Developing 'mobility as a service' models that allow users to access diverse forms of transport as their needs vary (including car sharing).[75]
- Integrated urban planning to promote denser mixed-use neighborhoods (where jobs, shops and recreation are found closer at hand) that are connected to the wider city by public transport.[76]
- Adoption of zero-emission vehicle technologies and the phase out of internal combustion engine vehicles.[77]

Connected vehicles (which communicate with each other and/or with traffic control systems), and autonomous vehicles (which could ultimately drive themselves), are currently the focus of intensive research and have the potential to transform the transport landscape.[71,78,79] These technologies could make a substantial contribution to emissions reductions, but their ultimate impacts will depend on how they are deployed.

Approaches cited above that reduce road vehicle kilometers travelled are important, even as zero emission vehicles gain market share.[198] They can promote more livable cities and improved quality of life. Until the electricity supply and auto production chains are completely decarbonized even zero-emission vehicles are associated with some GHG emissions. Moreover, the electricity system will assume many additional loads during decarbonization (building heating, industrial processes), and this expansion of electricity provision will require significant investments in physical resources and capital. So, reversing the continuing growth in road vehicle kilometres travelled can ease the electricity supply challenge during accelerated decarbonization.

Nevertheless, the switch to zero emission vehicles and the phase out of the internal combustion engine is a critical strategic step to accelerate the transition in personal transport.

Even with the adoption of all the travel reduction and modal shift options listed above, the structure of our cities and patterns of daily life mean that millions of personal vehicles will remain on the roads for the foreseeable future. And shared, connected, or autonomous vehicles must also be zero emission if they are not to contribute to climate change. A shift to zero-emission passenger vehicles will break dependence on gasoline for mobility and alter the economic and political position of the oil industry. And the technologies that can accelerate this transformation over the coming decade are already mature.

Heavy trucks account for 40% of freight movement in Canada (as measured by ton kilometers) but generate nearly 90% of freight related GHG emissions. This is because of the comparative efficiency of moving freight by rail. Many approaches can contribute to reducing emission in the freight sector (including a modal shift towards rail), but the critical element for systems change is the adoption of zero emission vehicles and the phase out of diesel trucks.

BOX C

Decarbonising long-distance land transport

RAIL: Overhead electric, battery electric or hydrogen fuel cell locomotives could replace current diesel electric trains. Because of Canada's large distances, and especially for freight, hydrogen fuel cells look particularly promising today.

AIR: Bio-based aviation fuels, or battery electric propulsion (for shorter flights), but widespread adoption is one or more decades away. Displacing passengers from air to high speed rail for journeys up to 600 kilometers. Canada is the only developed country where freight currently has priority over passenger trains on the rail network.

5.2.1 **Sector:** Light-duty vehicles

Function	Mobility for work, shopping, social activities, recreation
GHG emissions	13% of Canadian emissions (54% of transportation emissions), plus the emissions generated in the oil and gas sector to produce this gasoline
Options for decarbonization	Electric vehicles; hydrogen fuel cell vehicles
Stage of transition	Electric vehicles: early diffusion phase; Fuel cell: emergence
Nature of the problem today	Up-front costs of zero-emission vehicles; limited charging/refuelling infrastructure; resistance by established manufacturers (supply)
Other systemic issues	Air and noise pollution, costs of ownership, traffic congestion, car-dependent land-use patterns
Opportunities and concerns	For users: reductions in fuel costs, reduced maintenance, reduced total cost of ownership, enhanced vehicle performance. For communities: reduced air pollution. Economic development: business opportunities in the EV value chain; being prepared for vehicle connectivity and automation Risks: decline in existing Canadian auto sector if sufficient investment in EV value chain fails to materialize
Priorities for action	Subsidies for EV purchases; infrastructure investment for charging; government fleet and procurement standards; zero-emission vehicle standards; gasoline/diesel phase-out date; measures to ensure charging at multi-unit residential buildings; building code adjustments. Strategic intervention to build out supply chain for zero-emission transport manufacture
Longer-term issues	Managing grid integration; complementary technologies, smart charging, vehicle to grid, advanced materials; integration with other approaches including: active mobility, public transit, mobility as a service and connected and autonomous vehicles
Indicators of progress	Percent of zero emission vehicle sales; infrastructure build out; value-added in zero emission vehicle production

Roughly 85% of Canadian households have at least one car or light duty truck (SUVs, pickups, vans) and the total number of vehicles continues to increase. Between 2008-2018 the vehicle population grew by 18% (from 19.6 million to 23.1 million), with light-duty trucks making up the fastest growing segment.[64]

Automobile production is a globalised industry dominated by a handful of large multinational companies. With its close connections to related sectors (including oil, steel, chemicals, glass and plastics), the auto industry has been a pillar of economic development for more than century and, after a house, a car is usually the largest consumer purchase.[80]

Canada has a substantial auto manufacturing sector located mainly in Southwestern Ontario. Five multinational companies (Fiat Chrysler, Ford, GM, Honda and Toyota) have vehicles assembly operations. There are also major parts manufacturers, associated machine tool and electronics firms, and testing and R&D facilities. The industry directly employs more than 125,000 workers and makes a $19 billion contribution to GDP. Canadian automotive production is fully integrated with the North American market and provides the country's second largest export (after oil and gas). Particularly since the 2008 recession vehicle production has declined and the sector has been shedding jobs. As a second-tier producer Canada has had to continuously adjust its automotive policy regime to maintain the viability of the domestic industry.

Over time the fuel efficiency (and hence GHG performance) of internal combustion engine vehicles has improved, particularly as automakers have come under regulatory pressure motivated by concerns over air pollution. But movement to net zero GHG emissions requires a fundamental shift in vehicle design. Electric propulsion, in battery electric vehicles or hydrogen fuel cell vehicles, provides the most convincing technological solution, but also promises other benefits including lower lifetime vehicle costs,[194] improved performance, reduced maintenance and elimination of conventional air pollutants (particulates, nitrogen oxides, VOCs, etc.) For an evaluation of the difficulties with alternative emissions reduction approaches — such as blending ethanol with gasoline, switching to natural gas, gasoline/electric hybrids, biofuel vehicles, or synthetic (non-fossil derived) gasoline — see the assessment table below.

NET ZERO PATHWAYS

The transition to electric mobility is already underway. Battery electric vehicles have emerged as the favored design for zero-emission light duty vehicles and have entered the diffusion phase. Vehicle functionality has improved, and producers are benefiting from improving economies of scale, infrastructure roll out, complementary innovations, and favorable regulatory and policy frameworks.[81] Hydrogen fuel cell vehicles remain at the emergence phase. Over the past decade international electric vehicle (EV) production has ramped up to pass more than 2 million a year in 2018. Battery prices have dropped by over 80%, while vehicle range has steadily improved. Globally, EVs make up about 2.5% of automobile sales but have taken a larger share in a few lead markets (Norway: 56%; Sweden 11%; China 5%). Electric vehicle figures include both battery electric (fully electric vehicles) and plug-in hybrid electric vehicles (which have an auxiliary gasoline motor that can charge the battery). The balance of sales between the two types is evolving toward the fully electric form (nearly 75% of global EV market share in 2019). Over the past few years, the major automotive producers have committed to an electric future. But while the direction of travel is clear, the pace of change remains very much in question.

The main barriers to broader EV uptake include higher purchase cost and limited range as compared to internal combustion engine vehicles, and lack of charging infrastructure. Consumers are also concerned over performance in cold weather, charging times, and the narrow range of models available (particularly in the light truck market segment). In Canada there is increasing evidence that demand is outstripping supply with long waiting times for vehicle delivery.[193]

To date innovation has primarily been driven by outsiders (Tesla, China), while the dominant automotive producers have been resistant to shift from the internal combustion engine that has been so profitable. Incumbents have substantial physical and intellectual capital (patents, know-how) sunk in existing designs. EVs are quite different from ICE vehicles and will achieve their full potential with novel designs (rather than with the insertion of a battery and electric motor into an existing model). After many years of keeping a watching brief the major producers have now committed to electrification, but (particularly in North America) they would like to spread the transition over multiple decades.

Building the EV value chain in Canada is essential both to accelerate the market penetration of electric vehicles and to secure economic opportunities in a net zero future. Automobile production in Ontario is today based almost entirely around internal combustion engine vehicles as international automakers have preferred to concentrate EV innovation in their home territories or in major markets such as China. Policy makers in Canada have been hesitant to drive EV uptake if it is seen as hastening the decline of an established industry. As the global transition in this sector gathers pace, existing manufacturing jobs are subsisting on borrowed time. For economic and political reasons building EV market share and expanding domestic industrial capacity go hand in hand. If there is to be a vibrant Canadian auto industry in the future, policy must embrace both goals.

While its domestic market is small, Canada potentially enjoys advantages in the race to build production capacity for electrified transport. These include mineral resources, the mining, processing, and electro chemical capacity required for battery manufacture, as well as strengths in vehicle assembly, a skilled workforce, and R&D capacity. Pioneering research on the development of lithium-ion batteries and electric drive chains took place in Canada, as well as ongoing research on vehicle connectivity and autonomy. Portions of the value chain are already growing, particularly in the manufacture of busses, medium duty trucks and specialized industrial and off-road vehicles.

Canada cannot expect to be a first rank player in the global automotive industry (like Germany, China or the United States), but even a second-tier position with a strong presence in particular niches, could yield annual markets worth tens of billions of dollars. Attracting foreign partners can speed up development. It is not clear that incumbent auto makers will dominate EV production in the future. New entrants are joining the sector, and battery and drive chain technologies are still at the beginning of their development curves. If Canada is to have a place in this future, governments must take an active role to chart a path forward, build capacity, attract capital, and support training and R&D. So far, the Quebec government has taken several important initiatives, but despite some recent announcements, the Ontario and Federal governments still appear to lack focus, have been discouraged by existing incumbents, and hampered by a reflex of 'letting markets decide' or (since Biden's election) waiting for the US to take the lead.

SHORT AND LONG TERM PRIORITIES

Federal and provincial governments have offered incentives to encourage EV purchase, and initial investments have been made in vehicle charging networks. Quebec and British Columbia have had the most active policy supports with 8.3% and 5.9% of new vehicle sales in 2019 respectively. [82] As production volumes have gone up prices are falling, but purchase supports will be required for some time. Experience from other countries suggest a basket of measures are most effective to accelerate sustainability transitions. For EVs these can include subsidies for individual and fleet purchases, public procurement policies that favor EVs, investment in charging infrastructure, and public education around the benefits. Zero emissions vehicle standards (that compel suppliers to meet a target percentage of emission free vehicles in their annual sales) can be effective. Strengthened emissions standards for gasoline and diesel engine cars can also help by raising the price of traditional vehicles. Announcement of a phase out date for GHG emitting vehicles sales sends a powerful signal to producers and consumers.[83–85]

Over the next few years battery prices are expected to continue to fall, and vehicle range will grow. A wide variety of SUVs, vans and pick up trucks will enter the market, although prices for these will be relatively high. Improved charging infrastructure is critical to widen EV appeal. Public investment is important but so is development of business models to encourage private investment. Catering to adopters living in multi-unit dwellings is particularly challenging,[86] as 'range anxiety' has now been replaced by concerns over 'charging deserts' for urban dwellers.[87] So building codes, regulations and condo rules for multi unit dwellings must be updated to be 'EV ready'.

Measures to encourage vehicle uptake should be coupled with strategic intervention to build the EV supply chain, so that the positive economic and political synergies between EV market penetration and EV-related economic activity can be achieved. This can also strengthen Canada's presence in connected and autonomous vehicle development. Time is short to take maximum advantage of potential comparative advantages.

Longer-term issues include: ensuring sufficient grid capacity, as an increasing share of the transport load is assumed by electricity; managing charging demand and possible 'vehicle to grid' energy storage applications; 'second life' battery applications and battery recycling;[191,192] complementary transportation demand management, especially expansion of public transit and transit-integrated land use planning; and integrating electrification with approaches related to mobility as a service, connectivity and automatous vehicles.

Continued fossil energy presence on the electricity grid, and the GHG footprint of EV manufacturing and end-of- life vehicle disposal, are sometimes advanced as reasons not to accelerate EV adoption. But the Canadian grid is already largely decarbonized, and research suggests that even in provinces with higher GHG intensity of electricity supply EVs will bring short term emissions reductions. But the real issue is not short-term emissions but tipping the transport system away from dependence on fossil fuels. Driving up EV market share accelerates this process, and in the decade or two that it will take to electrify the light vehicle fleet, full decarbonization of electricity supply will proceed.

Similarly, it will be by decarbonizing the grid, and addressing energy and process emissions in the mining industry, steel, chemical and plastics production, and in battery production and recycling that GHG emissions embodied in vehicles can progressively be addressed.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Light-duty vehicles**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Electric Vehicle									
Battery electric	Early maturity but with plenty of room for development in batteries and power trains to improve functionality and cost.	Purchase cost still higher than ICE vehicles but improving; in some cases, lifetime ownership costs already lower.	No particular concerns	Yes. Continuous improvement in range. Some concerns over operation in extreme weather.	Yes. Full net zero dependent on decarbonizing grid electricity and decarbonizing supply chain (net zero lifecycle vehicles).	Compelling to emerging producers. Considerable residual opposition from incumbents including dealerships	Improved driving, lower maintenance costs, no air pollution, noise reductions. Prepared for connected and autonomous technologies. Environmental risks associated with battery production and disposal, and safety	Potential jobs in supply chain: mining (lithium, cobalt, copper, etc.), material processing, battery production, auto assembly, research, design, ancillary industries. Links to connected and autonomous vehicle development	High. Potentially part of net zero emission world
Plug in hybrid electric	Early maturity with some development potential	Purchase cost higher than ICE vehicles. Two power trains mean less maintenance gains than battery electric.	No particular concerns	Yes. Range concerns eased by gasoline auxiliary motor.	Not compatible with net zero because of gasoline engine but can help accustom consumers to EVs and weaken dominance of ICE vehicles	Appealing to consumers who want to go electric, but need reassurance on range and reliability	Improved driving, reduced air pollution. GHG emissions Environmental risks associated with battery production and disposal.	Some potential jobs in supply chain (see for battery electric above). But widely seen as intermediate/transitory technology.	Medium Can facilitate transition to battery electric
Hydrogen Fuel Cell									
	Late development phase. Light duty vehicle design not yet stabilized. Hydrogen distribution network virtually non-existent.	Low at present. Vehicle purchase cost higher and distribution of hydrogen very expensive and currently impractical for light duty vehicles.	Some concerns over safety of hydrogen fueling	Yes. Good power and range.	Yes. Full net zero dependent on decarbonized hydrogen production for renewable, nuclear or methane with CCS and offsets.	Most stakeholders now backing battery electric for light duty vehicles. Some support in specific markets (Japan, California). May have potential for fleet vehicles because of centralized fueling model	Improved driving, lower maintenance costs, no air pollution, noise reductions.	Potential jobs in manufacturing and building out hydrogen economy.	Medium/high Potentially part of net zero world. But less compelling for this use today than battery electric
Ethanol									
Blended with gasoline	Mature	No vehicles cost premium. Fuel more expensive than gasoline. But frequently mandated.	Yes, widely practiced	Yes. slightly reduces octane level.	Blends not compatible with net zero emissions or with a transitional role because full ethanol endpoint is not viable (see below)	Appealing to some producers and those seeking symbolic emissions reductions	Does not eliminate air pollution. Potential land use problems. GHG reductions depend on proportion of blend, bio feed stock source and energy inputs.	Not in a net zero economy	Not a priority

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Light-duty vehicles**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
100% ethanol	Mature	Small vehicle cost premium, Fuel not currently competitive with gasoline. Prices depend feedstock.	No particular concerns	Yes. Lower energy density than gasoline.	In principle, if biomass is grown and regenerated in a net zero way. Energy inputs and vehicle production chain would need to be net zero. But not practical at scale. Land use conflicts, biodiversity pressures.	Interest from agricultural producers and some fossil energy companies.	Can use existing engine technology and parts of fuel distribution network. If energy inputs come from bio sources this could be combined with CCS for negative emissions.	Potentially new markets for biomass.	Low Could play some part in particular contexts but not at scale.
Natural gas									
Compressed or liquified NG	Mature	Natural gas is currently inexpensive, but compression and distribution costs are high	No concerns, except it is a fossil fuel	Yes. Similar to gasoline or diesel vehicles concerning power and acceleration.	No. Only 6% to 11% lower levels of GHGs than gasoline throughout the fuel life cycle.	Some interest from manufacturers, fleet operators and existing gas suppliers	Lower fuel efficiency that ICE. Air pollution not addressed.	Short term expansion of NG markets	Not a priority Fossil fuel option
Renewable NG (biogas)	Mature at small scale	More expensive that natural gas. Limited sources of feedstock.	No particular concerns	Yes. Similar to gasoline or diesel vehicles with regard to power and acceleration	Not practical at scale. Lack of necessary feedstocks. Applicable in specific contexts (for example, on farm use).	Weak interest from manufacturers. Some interest from fleet operators, potential biomass suppliers, and gas distributors.	Can use existing engine technology and fuel distribution network. Air pollution not addressed	Some local opportunities in specific industries (farming, forestry, food processing, waste disposal)	Very low. Could play some part in a net zero economy but not at scale.
Synthetic NG (power from decarbonized sources, carbon from biomass or air capture)	Early research stage	Very high costs	No particular concerns	Yes. Similar to gasoline or diesel vehicles with regard to power and acceleration	In principle, but requires net zero hydrogen (from methane with CCS and offsets) or renewables, or nuclear, and biomass or air capture	Still at research phase	Can use existing engine technology and fuel distribution network; air pollution not addressed	Remote	Very low. Could be part of net zero economy but a long trajectory
Gasoline hybrids									
Gasoline engine with battery storage and regenerative braking	Mature	Yes, now in mainstream production	No particular concerns	Yes. Saves gasoline, improved acceleration	No. powered by fossil fuels	Already in mainstream production but limited perspective in net zero world	Uses existing gasoline infrastructure. Does not address air pollution.	Not in a decarbonizing world	Not a priority Fossil fuel option
Synthetic gasoline									
Energy from zero carbon sources, carbon from bio or air capture	Early research stage	Currently very high costs	No particular concerns	Same as fossil gasoline	In principle, but requires cheap clean hydrogen and carbon from bio feedstocks or air capture.	Unclear	Uses existing gasoline engines and fuel distribution network. Does not address air pollution.	Remote	Very low. Transition to electric vehicles already underway

5.2.2 Sector: Heavy trucks

Function	Transportation of freight by heavy truck
GHG emissions	9% of total Canadian emissions in 2018 (42% of transportation emissions), plus the emissions generated in the oil and gas sector to produce diesel
Options for decarbonization	Hydrogen fuel cell trucks; battery electric trucks; catenary electric trucks
Stage of transition	Emergence
Nature of the problem today	Up-front costs of vehicles; weight of batteries; fuel production and/or infrastructure; uncertain investment environment
Other systemic issues	Noise and air pollution, congestion, poor load factors, labour shortages, small profit margins
Opportunities and concerns	For users: reduced maintenance, improved vehicle performance. For communities: reduced air and noise pollution. Economic development opportunities: Fuel cell tucks: manufacture of fuel cells, vehicle assembly, hydrogen production, accelerating emergence of hydrogen economy; Battery and catenary trucks: battery manufacture, vehicle manufacture. Concerns: hydrogen safety; appropriate shift to low and zero emission hydrogen supply.
Priorities for action	Policy supports for (a) vehicle development (optimising fuel cell and electric motors for heavy duty road vehicles (b) hydrogen production (from methane with CCS and by electrolysis from renewables) and (c) build out of fueling infrastructure along major transport corridors. These can include R&D subsidies, support for fleet conversions and terminals, public procurement policies, zero emission vehicle standards, development of standards and safety rules, and cross jurisdictional coordination.
Longer-term issues	Managing grid burden and/or stepwise development of hydrogen production and consumption; integration with connected and autonomous vehicle technologies; transition to zero emission hydrogen (either by ensuring offset availability or shifting entirely to production from net zero electricity).
Indicators of progress	Percent of zero emission vehicle sales; scale of infrastructure build out; value added in zero emission vehicle value chain; carbon intensity of grid or hydrogen used for heavy vehicles

Heavy road freight has increased over the past thirty years as production and consumption has grown, supply chains have become more globally integrated, and Canada has pursued its trade-oriented development trajectory. Trucking is especially prominent in Central Canada, and in 2018 more than half the total merchandise exports by value (excluding oil and gas) left this region by road.[64] Today, the trucking industry is entirely dependent on diesel fuel, which contributes to air pollution (nitrous oxide and particulates) as well as GHG emissions, and imposes high engine maintenance costs on firms.

Canada's road freight sector is large and highly fragmented. More than 40,000 general and specialized freight companies operate a total fleet of about 300,000 heavy-duty vehicles.[88] In

2017, these companies employed about 200,000 Canadians. The road freight sector is facing labour shortages, in addition to other challenges like small profit margins and poor load factors.

Digital technologies have impacted trucking through the tighter supply chain management and logistics and the rise of e-commence, more recently with increasing traffic movements in urban areas from direct-to-home delivery. Emerging technologies, including software analytics, applications of AI and connected and autonomous vehicles, are expected to impact the sector in the future.

NET ZERO PATHWAYS

The transition to net zero emission heavy trucking has hardly begun, with the leading technological options — hydrogen fuel cell, battery electric, and catenary trucks — still in the emergence phase. All options employ electric drive trains, but the first produces the electricity from hydrogen fuel cells, the second draws power from batteries, and the third from overhead wires. Each enjoys the electric motor advantages of high torque, lower maintenance, low noise, and an absence of air emissions. All cost more today than diesel trucking, and the requisite fueling infrastructure has yet to be built out.[200] In each case, the net zero emissions potential ultimately rests on decarbonization of the relevant energy carrier (grid electricity or hydrogen). Start-up firms (Tesla, Thor, Nikola) and well-established manufacturers (Toyota, Daimler, Siemens) have begun to develop prototypes and/or bring early models into service.[89]

There are advantages and difficulties with each option. Although battery electric trucks make sense for light and medium duty freight applications (for example, urban delivery vehicles or municipal fleets), for heavy duty and long distance transport the battery weight and charging times pose a significant challenge. Current charge densities would require large batteries that would dramatically reduce vehicle carrying capacity. In Canada there are also concerns about performance in very cold weather (which drains battery charge). So, the solution that works for light and medium duty vehicles is not immediately transferable to heavy freight. Catenary trucks solve the weight problem by drawing power from overhead cables (like a trolly bus), with a smaller on-board battery for operating on roads without wires. The difficultly here is the cost of installing the overhead network, which is particularly acute in a country like Canada with its vast distances and multiple jurisdictions (which may or may not have made the required infrastructure commitment). Finally, for hydrogen fuel cell trucks the major problem is the production and distribution of low-cost low GHG emission hydrogen.[90]

In the Canadian context hydrogen fuel cell trucks are more attractive, particularly in Western Canada. These vehicles have functional advantages in Canadian conditions (very heavy loads moving over large distances with weather extremes). But they also offer significant development opportunities that could accelerate Alberta's movement away from an oil-based export economy, thus facilitating the net zero transition for the whole country. If Alberta could become a producer and exporter of low-cost net zero emission hydrogen there would be a way for the province to continue as an energy powerhouse even in a decarbonized global economy.[91,92]

Today hydrogen is produced commercially from natural gas (steam-methane reforming) for use in bitumen upgrading, fertilizer manufacture and the chemical industry. Alberta is among the lowest cost producers in the world. Applying CCS to this process can produce very low GHG emission hydrogen, but additional offsets would be required to get to net zero. Hydrogen can also be made from renewables though electrolysis without producing any GHG emissions, although the process is much more expensive. Alberta possess excellent solar, wind and geothermal potential, and a build out of renewables combined with falling electrolysis costs could make the province a major producer of clean hydrogen. The relative significance of these two hydrogen streams will evolve over time, depending on technological development trajectories, comparative costs, the stringency of GHG abatement regimes and the availability of offsets. Many countries are showing interest in hydrogen and there is an opportunity if Alberta moves rapidly to exploit its comparative advantage.[90,92]

A challenge in building a hydrogen economy has always been the stepwise development of demand and supply, so economies of scale can kick in and hydrogen production and distribution costs brought down. Heavy trucks can supply an 'anchor tenant' for the hydrogen economy, as the fueling infrastructure is built out along major transport corridors. The availability of cheap hydrogen can in turn facilitate decarbonization in other transport applications (railways, heavy construction equipment), in difficult to decarbonize industrial sectors (cement, steel, chemicals), and may find application in building heating.

Battery electric trucks can be expected to improve performance over time, as energy densities rise and weight declines, and new battery chemistries come to market. The head start which battery electric has achieved in personal vehicles, gives it an advantage in the shorter haul and medium duty market (where battery weight is not so debilitating), particularly for manufacturing companies active in both market segments. Over the longer term this option could also become more attractive for heavy duty vehicles.

PRIORITIES FOR ACTION

Coordinated action and multiple policy initiatives are required to advance the net-zero transition for heavy road transport beyond the emergence phase. Manufacturers and fleet managers currently face limited incentives to move away from diesel trucks. Vehicles are still at the development or very early production stage; purchasing costs are much higher and fueling infrastructure is absent. Uncertainty about the technology that will come to dominate the market, and over the pace of change, generates substantial investment risk for both manufacturers and vehicle purchasers. On the other hand, the market structure of the heavy freight sector is very different from the personal vehicle market. With more local production of vehicles adapted to specific needs, and larger blocks of concentrated buyers (big trucking companies, major retailers, etc.), the opportunities to coordinate change and scale-up once the transition gets underway are significant.

For battery electric trucks support for accelerated research and development of battery technology is critical. Measures to encourage the deployment of medium duty vehicles (medium trucks, busses, utility vehicles such as garbage trucks, snow removal equipment, etc.) can accelerate learning by doing that may allow a gradual scale up into the heaviest vehicles. Incentives for fleet purchases, public procurement mandates, investment in charging infrastructure at depots and along strategic transportation routes are important for accelerating change for heavy trucks.[93,94]

For hydrogen fuel cell heavy trucks action is required (a) to optimise fuel cell and electric motors for heavy duty road vehicles (b) develop hydrogen production (from methane with CCS and renewables) and (c) build out fueling infrastructure along major transport corridors. The deployment of fuel cell heavy vehicles makes sense as part of a larger strategy to develop the hydrogen economy, and here a leading role must be assumed by governments at multiple levels. The creation of various consortia including major trucking firms interested in moving their fleets to zero emission vehicles, companies that can supply hydrogen, fuel cell and vehicle manufacturers, researchers and governments will be required to advance across the whole system. Financial support for fleet conversions, public procurement, build out of fueling and hydrogen distribution infrastructure will be required. There are also standards and safety issues that must be addressed.

All pathway options can be supported by strengthening fuel efficiency standards for diesel trucks, increasing the carbon price on diesel fuel, and applying low carbon fuel standards. At a later stage, a low carbon vehicle standard may also be appropriate (as California is already considering).[202]

Because long distance freight moves east/west across inter-provincial boundaries and north/south across the Canada/US border, inter-provincial and international cooperation will be important. Efforts must be made to coordinate cross-jurisdictional rollout of fueling infrastructure and regulatory standards.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Heavy-duty vehicles** (Long-haul freight)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Hydrogen Fuel Cell									
	Fuel cells: mature but not scaled up. Hydrogen from methane: mature. Hydrogen from electrolysis: still developing Fueling infrastructure virtually nonexistent	Vehicle purchase cost higher and distribution of hydrogen very expensive. Hydrogen from methane (even with CCS) currently much cheaper than hydrogen from electrolysis	Some concerns over safety of hydrogen fueling	Yes. High torque	Yes. If hydrogen is made from decarbonized electricity such as renewables or from fossil sources with CCS and offsets. Longer term viability of fossil-based hydrogen depends on CCS and offset availability	Compelling to some truck manufacturers and trucking firms.	Improved driving (torque), lower maintenance, no air pollution, noise reductions. Concerns with fuel cell recycling. Potentially 'anchor tenant' for hydrogen economy	Opportunities for fuel cell manufacture, vehicle manufacture and hydrogen production (especially for Alberta with hydrogen from methane and wind/solar/geothermal hydrogen production)	High Potentially part of net zero emission world.
Electric									
Battery electric	Still emerging. Energy densities of current battery technology needs improvement. New chemistries may be required.	Higher costs of vehicles as compared to diesel	No particular concerns	Not at present. Good torque but limited load capacity because of batteries. Concerns over cold weather	Yes. Ultimately depends on net zero electricity and decarbonized supply chain (steel aluminum, plastics)	Potentially compelling if battery charge/weight issue addressed	Improved driving (torque), lower maintenance, no air pollution, noise reductions	job opportunities for research, design, assembly, and maintenance	High Potentially part of net zero emission world
Catenary electric	Technologies mature when deployed in other applications (trolly buses). Still at pilot stage for this application	High cost of vehicles compared to diesel. High cost of infrastructure roll out with Canadian distances	Uncertain	Yes. If infrastructure existed at appropriate scale. Range concerns for battery driven mode	Yes. Ultimately depends on net zero grid GHG electricity and decarbonized supply chain (steel aluminum, plastics)	Potentially compelling if infrastructure built out But concerns over vehicle flexibility off the catenary network	Improved driving (torque), lower maintenance, no air pollution, noise reductions Concerns over impact on other road users.	job opportunities for research, design, assembly, and maintenance	Medium Potentially part of net zero emission world
Biodiesel									
	Mature	More expensive that diesel because of distributed nature of the resources and costs associated with handling, transport and processing	No particular concerns	Yes. Similar torque and horsepower as diesel-powered engines	Perhaps. Depends on feedstock, processing, distribution. But lack of feedstock precludes general application	Somewhat compelling for particular producers and consumers.	Can use existing infrastructure. Safer to handle and transport than diesel. But does not address air and noise pollution. Negative impacts of land use change.	Potentially new markets for biomass.	Very Low Not scalable Does not facilitate transition. Air pollution emissions

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Heavy-duty vehicles** (Long-haul freight)

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Natural gas									
Compressed or liquified NG	Mature	Natural gas is currently inexpensive, but there are also compression and distribution costs	No concerns, except it is a fossil fuel	Weak: low torque, power	Not compatible with net zero (30% GHG reduction from diesel).	Weak from trucking firms. Interest from existing gas suppliers	Can use existing pipeline infrastructure and engine designs. Air pollution not addressed.	Short term expansion of NG markets	Not a priority Fossil fuel option Does not facilitate transition
Renewable NG (biogas)	Biogas production technologies still developing	Medium	No particular concerns,	Weak: low torque, power	Not practical at scale. Lack of necessary feedstocks. Applicable in specific contexts.	Weak from trucking firms. Some interest from possible biomass suppliers.	Can use existing pipeline infrastructure and engine designs. Air pollution not addressed	Some local opportunities	Low Not scalable. Does not facilitate transition. Air emissions
Synthetic NG (power from low-carbon sources, C from bio or air capture)	Early research stage	Very high costs	No particular concerns,	Weak: low torque, power	In principle, but requires cheap H2 production and cheap air capture to be competitive	Still at research phase	Can use existing pipeline infrastructure and engine designs. Air pollution not addressed	Remote	Low Very immature technology Air emissions

5.3 **Sector**: Buildings

Function	Structures including residences, places of business, schools, hospitals and other public facilities.
GHG emissions	92Mt CO_2e (2018); 13% of of total national emissions 47 Mt CO_2e homes; 45Mt CO_2e commercial and institutional buildings
Options for decarbonization	Replace fossil end uses (principally gas for heating); increase energy efficiency of all buildings (new and old); reduce embodied emissions in building
Stage of transition	Design, construction and retrofitting to net-zero buildings: emergence stage. Individual technologies such as enhanced heat pumps: entering diffusion.
Current obstacles	Cheap price of natural gas; up-front capital costs for net zero construction or renovation; shortage of trained workforce; insufficient incentives and coordinated standards to drive innovation; conservative industry structure and practices.
Other systemic issues	Affordability of housing; lack of public housing; electricity options for remote communities; construction related waste; developer dominated urban planning, lack of real estate industry interest in energy performance and energy performance disclosure.
Opportunities and concerns	Consumers: reductions of fuel costs and utility bills over the long run; opportunity to improve indoor air quality and general comfort. Economic development: employment opportunity in low-carbon retrofit and construction; business opportunities in net zero equipment (e.g., heat pumps); green real estate market; export opportunities for low-carbon building materials; possible build-out of hydrogen economy.
Priorities for action	Adoption of progressively more stringent codes for new builds, and regulatory standards to drive improvement in existing buildings; use public procurement to support sector transformation; financial vehicles to mobilize private capital and organize pilots to scale up deep retrofits; mandatory building/energy emissions labelling; support R&D for net zero building technologies adapted to Canada's climate (eg: cold climate heat pumps); train Canada's labor force for low carbon building design, construction, retrofit and maintenance.
Longer-term issues	Affordable net-zero housing; efficiencies through district heating
Indicators of progress	Share of electricity in building's energy consumption; annual retrofit rate; transparency around embodied carbon in building materials.

Buildings are essential to the comfort, health, and economic productivity of Canadians. The sector contributes to GDP directly through real estate, rental, and leasing income (13% of Canada's GDP), and through the construction industry, which makes up 7 % of Canada's GDP (although this figure includes infrastructure construction as well as buildings).[95] Real estate, rental and leasing markets are concentrated in key metropolitan areas. Nearly 1.5 million workers or 7.7% of the workforce were employed in the construction industry in 2019.

It is useful to distinguish residential properties from commercial and institutional premises.

RESIDENTIAL BUILDINGS

There were 15.5 million households in Canada in 2017, and almost 200,000 new homes are built each year as the population continues to grow.[215] More than 63% of Canadian families own their own home, with those in older age groups more likely to be owners.[96] More than half of these households (57% in 2016) are paying off a mortgage.[216] Single-detached houses represented 54% of all dwelling types in 2016 ,[217] but with the rise of condominium and apartment-based households this share has been declining for three decades. Large investment firms and property management organisations own many of the rental properties.

In recent years, house prices have risen faster than household income. While the median Canadian household income increased by 28% between 2007 and 2017,[218] house prices grew by 70%. According to the OECD, Canada's house price to income ratio was among the highest across member countries in 2019. Shelter was the largest item on household expenditure In 2017, accounting for 29% of the total consumption of goods and services, and mortgage debt is responsible for almost all of the recent increased debt burden of Canadian families.[97]

In contrast, most homeowners spend a small percentage of their income on utilities (water, gas, heating oil and electricity) which represent less than 3% of total household expenditures.[220] Electricity and natural gas are the primary domestic energy sources, with 41% and 42% of energy use coming from these sources, respectively.[98] Canada's has among the lowest residential electricity prices in the world, with monthly electricity bills for households with average consumption in different provinces ranging between $73 and $168.[99] Average natural gas bills range between $65 to $155 per month, significantly lower than European peer countries.[100] While Ontario has some of the highest electricity rates in Canada it, along with western provinces, enjoys among the lowest average household gas bills.

Energy use in the residential sector has increased by only 3% from 1990 levels (despite a 50% rise in the number of households), due to steady improvements in energy efficiency, particularly through the modernisation of building codes in some jurisdictions, the adoption of LED lighting across Canada, and improvements in the efficiency of equipment such as boilers and refrigeration.

COMMERCIAL AND INSTITUTIONAL BUILDINGS

There were more than 480,000 non-residential buildings in Canada in 2014. The floor space of commercial building has risen by 48% since 1990 as Canada's economy has grown, and international companies continue to expand in Canadian cities. Office buildings, warehouses and non-food retail stores make up the biggest shares of non-residential buildings, accounting for 20%, 13%, and 13% respectively.[101]

Commercial buildings are generally owned by private investors, and office and retail rents have risen rapidly in recent years: by 10-20% across Canada between 2018 and 2019. Commercial real estate financing comes from a variety of institutional sources (including banks, insurance

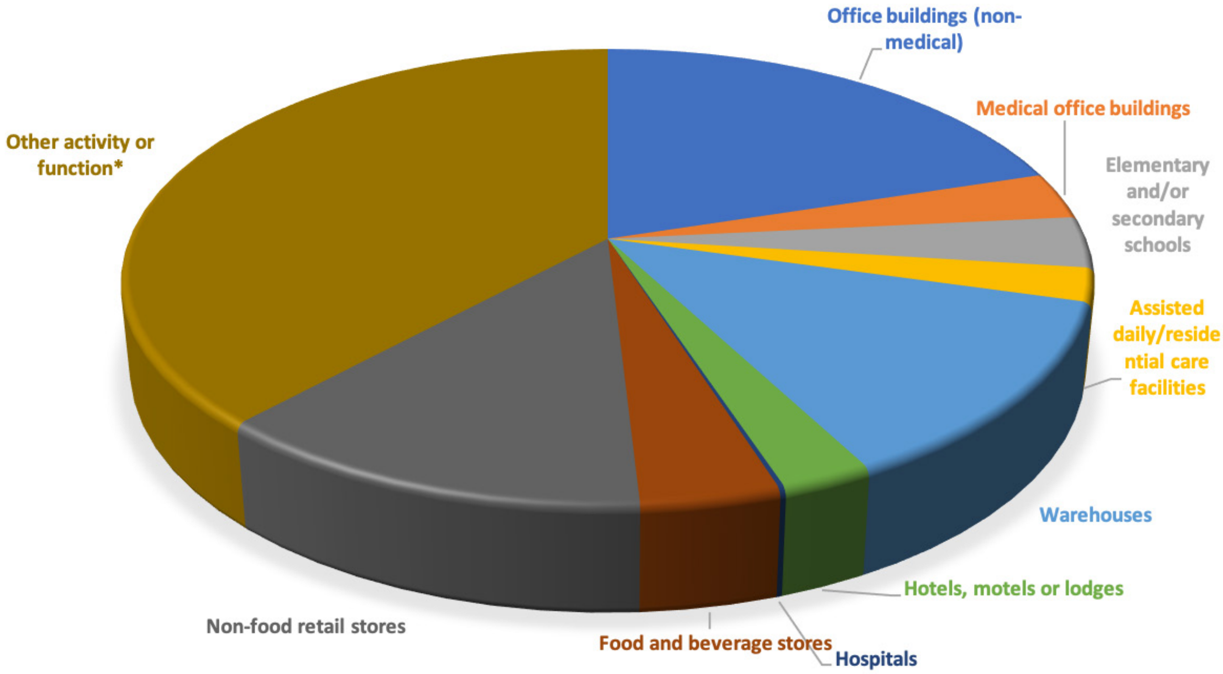


Figure 12. Commercial and industrial buildings by use.

Source: Natural Resources Canada[101]

companies, investment firms, pension funds and credit unions), with some larger players holding significant market share. There are few restrictions on foreign ownership, and major players include firms from Europe, the US and China.[102] Government offices, hospitals, schools, universities and research facilities, and other public buildings make up the institutional sector.[103,104]

NATURE OF THE PROBLEM

Buildings accounted for 13% of Canada's total GHG emissions in 2018 (92 Mt of CO_2e).[30] Approximately half of this came from the residential sector (47Mt), and half from the commercial and institutional sector (45MT). The 25% increase in emissions since 1990 has been driven mainly by commercial and institutional buildings. Energy is used mainly for space and water heating, with some cooling requirements.[29] Natural gas is the primary driver of emissions, followed by heating oil and some biomass (wood). About 10% of the sector emissions (9Mt CO_2e) comes from halocarbons such as hydrofluorocarbons (HFCs) used in cooling systems. Additional (indirect) emissions are associated with building construction (embodied in the materials, process or wastes), the upstream generation of electricity used in buildings, and the broader design of the built environment (for example, transport related to urban sprawl). Buildings account for half of Canada's domestic use of concrete and 8% of its iron and steel (GHG intensive materials) and construction and demolition waste makes up as much as a third of the municipal solid waste disposed in landfills.

Challenges to transforming the building sector today include:

- The difficulty of both dramatically improving the design and construction of new buildings and of adapting millions of existing structures to net zero standards. In some cases, outmoded buildings can be replaced, but our cities have been built out over decades and centuries, and a deep and aggressive rate of retrofit will be needed to decarbonise the sector.
- The relatively cheap cost of natural gas in Canada which discourages investment in energy efficiency (building insulation, more efficient heating units), and fuel switching to electricity. Energy efficiency is not a high priority for consumers when they choose a home or consider value-added renovation to an existing property. Similarly, commercial, and institutional building owners and managers have paid relatively little attention to monitoring energy performance. Natural gas and electricity prices vary from province to province, but the relatively low gas prices in Ontario and Western Canada make displacing gas a challenge. Because Western Canada is a large gas producer the issue is also politically charged. As recently as 2016 the Ontario government backed away from a proposal to phase out gas in new construction after 2030.
- The difficulty of financing the upfront costs for energy retrofits (even when payback periods are short) because of high levels of household dept and the absence of dedicated financing

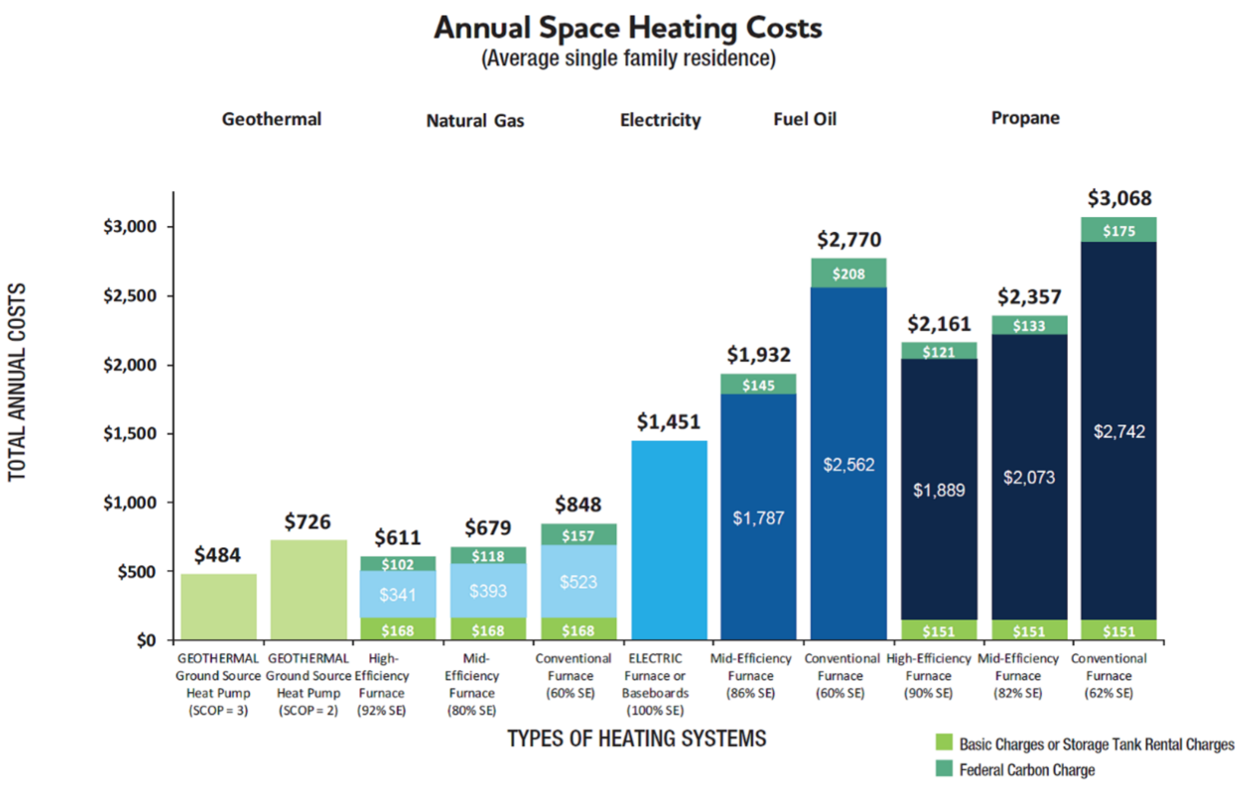


Figure 13. Costs of heating options in Manitoba for an average family home.

Source Manitoba Hydro.[241]

mechanisms. This is particularly true for lower-income households. According to the OECD, 20% of poor households in Canada spend more than 40% of their income on housing costs. Mobilization of finance is also a problem for the commercial and institutional sectors.

- Structural characteristics of the sector which include: a highly fragmented construction industry, with a small number of very large companies and thousands of small firms and independent contractors; conservative industry norms, where builders tend to apply methods that have worked in the past and are hesitant to adopt innovative approaches.

Over the past few decades building energy efficiency and GHG emission profile has been a secondary concern in both the commercial and institutional, and the residential sectors. Given todays relatively inexpensive energy prices, low rates of carbon pricing and permissive regulatory environment, there has been little incentive for change.

NET-ZERO PATHWAYS

A transition to a net zero building sector requires the elimination of end use combustion of natural gas and heating oil, the phase out of climate forcing refrigerants, and the decarbonization of the electricity supply and construction processes, materials, and waste.

There are two critical pathway elements to achieve this transformation:

1. Replace fossil fuel end uses in buildings with net zero energy

Natural gas and oil currently supply about half of residential energy requirements (44% and 4% respectively),[221] and a little more in the commercial and institutional sector (52% and 10%).[222] Most is used for space and water heating, although some goes for appliances (cooling systems, stoves, dryers) and backup power systems. Net zero emission options for the future include fuel switching to electricity, biofuels, or hydrogen.[101]

Electricity is in some ways the most straightforward alternative. It already supplies about 40% of building energy needs, and many residential, commercial, and institutional buildings rely on electricity for space and water heating. But electricity is significantly more expensive than gas, and generalized reliance on electricity for heating would increase demands on the electricity grid. Although electric heating has traditionally taken the form of resistance devices (baseboard heaters or furnaces), ground or air source heat pumps can dramatically reduce cost. Heat pumps exploit a temperature differential to heat or cool living space and can cut electricity consumption by a third or more. Nevertheless, there are limits to the temperature range over which they operate effectively, they are not appropriate in all contexts, and the initial capital outlay (particularly for ground source models) is substantial.[105–107]

Buildings can also generate their own electricity. Rooftop solar panels are already a familiar sight in Canadian cities. But over the next decade a suite of novel 'building integrated photovoltaic' technologies (including roofing, glazing and facade materials) will be coming to market. When combined with passive energy design elements (exploiting solar exposure), and/or building envelope improvements that reduce heating requirements, these technologies may be able to displace a large fraction of the annual electricity load for many buildings. And this could relieve pressure for additional electricity generation or transmission assets.[108]

Biomass currently supplies about 7% of building energy needs. On the residential side this is mainly in the form of wood or wood pellets. Biomass is typically considered carbon neutral, but the actual emission footprint depends on fossil inputs to harvesting, processing and transport as well as sustainable production of the biomass. Assuming an economy wide movement to net zero, and appropriate harvesting and planting practices, much of these residual emissions could be eliminated. On the other hand, biomass combustion causes air pollution. There are competing demands for biomass supplies and uses for the land on which they are grown. And there are typically difficulties securing adequate and inexpensive local supplies. Moreover, solid fuels are less convenient that liquid or gaseous alternatives. It is therefore difficult to see how solid biomass could supply a much greater proportion of building heating needs in the future.

Another option is to exploit the existing natural gas distribution network but substitute a net zero gaseous fuel. This could be 'renewable natural gas' made by anaerobic digestion of organic wastes (from sewage treatment, municipal waste, agricultural wastes, landfill sites, and so on) or eventually 'synthetic natural gas' made by using low carbon electricity and biomass or direct air capture). Problems with renewable natural gas are cost and scalability. Mixing this product into the natural gas supply system today can secure marginal emissions reductions. But there is not enough biomass available to fully substitute renewable gas for the existing natural gas supply. So, while it may have applications in settings or regions with ample supplies and low demand (a farming community for example), it is unlikely to be scalable nationally. Synthetic natural gas is far from ready for market.

Finally, hydrogen could be distributed through a modernised gas grid. Provided low cost and GHG emission free hydrogen was available, this solution for meeting building heating needs would be scalable. End use appliances would have to be adjusted to burn hydrogen and specific safety concerns would have to be addressed. Hydrogen fuel cells could also contribute to management of building electricity supply (serving as a storage for building integrated renewable generation) and/or for back up power. The viability of deployment of a hydrogen building heating option at scale would depend on the overall evolution of hydrogen as an energy carrier, including cost effective net zero emission production (through electrolysis or methane reforming with CCS and offsets) and demand development in other sectors (heavy freight, industrial users, and so on).[109]

2. Improve building energy efficiency.

Whatever net zero energy carrier meets end use needs, enhanced energy efficiency can reduce demand pressure on fuel supplies and keep costs down for consumers. For example, energy efficiency measures can lower building heating loads, minimize demand on the electricity grid for new generation or transmission, help control electricity costs and reduce the price differential with gas.[110,111] New buildings can be built to high energy performance standards, with improved building envelopes, exploiting passive design principles, new materials, more efficient HVAC and lighting systems and smart controls.

Retrofitting existing buildings to improving energy efficiency is also crucial. The energy intensity of residential buildings varies considerably with new construction performing much better than those built before 1960.[223] Better windows, door, and exterior siding and caulking, additional insulation, improved envelope air sealing and roof structures, coupled with energy-efficient equipment can all significantly lower energy requirements.[112]

These two foundational elements — replacing fossil fuel end uses and dramatically raising building energy efficiency — form the foundation for transition pathways in this sector and can be pursued in an integrated manner in new builds and retrofits of the existing building stock.

Additional elements many of which link buildings to wider systems (electricity, transport, communities), include:

- Completing the decarbonization of the electricity supplied by the grid to buildings (discussed in Section 5.1).
- Replacing climate forcing chemicals used in building cooling systems with climate benign refrigerants and cooling technologies.
- Moving to net zero emission building construction, which requires:
  - reducing energy and process emissions of the materials incorporated into the building fabric (steel, concrete, glass, plastic, and so on), as well as components (HVAC systems, windows and doors, etc.). Most challenging are the bulk construction materials (concrete and steel). The two basic strategies available are: (a) decarbonize their production (discussed in Sections 5.4) or (b) employ substitute construction materials. For example, engineered wood can be used for structural members and floors displacing concrete and steel, actually sequestering carbon into the edifice
  - reducing energy emissions from the construction process such as excavation, and transport (see Section 5.2 on heavy transport)
  - managing construction (and demolition) waste streams
- Adjusting the overall design of buildings and the physical layout of communities and cities, to enhance well-being while promoting climate friendly patterns of living. Changes here could include mixed use community design with district energy schemes; urban densification (that makes mass transit more practical, and requires lower overall energy loads than detached suburban houses); provision of more communal areas, green spaces, allotments, and local work hubs that may encourage a trend towards smaller sized houses (with lower energy requirements) or teleworking (with decreased transport needs).

PRIORITIES FOR ACTION

Movement towards a net zero building sector requires action to address new builds and retrofits. The retrofit problem is larger as there are millions of buildings to deal with. The new build problem is urgent as we are constantly adding to the stock of high GHG emission structures.

Priorities for transforming this system include the adoption of net zero GHG emission building codes (focused on emission intensity not just energy performance) which progressively raise the bar for new residential, commercial, and institutional buildings, and the introduction of mandatory performance regulations for existing buildings to guide the systematic retrofit of these structures over coming decades.

Codes should leave open a range of options for heating, cooling, building envelope and other design criteria, but gradually raise the bar to net zero emission standards. In the residential sector, net-zero building codes need to be carefully coupled with policies to address the affordability of homes, which is why community design and district heating (e.g., to use waste heat from buildings or industrial processes) can be considered.

Incentives, regulations, education of the public, and workforce training should all be elements of the policy package directed to ensure the uptake of clean energy supply. Although technologies like heat pumps can already be cheaper to operate than natural gas or oil-based heating, upfront capital costs and ongoing concerns about the price of electricity remain barriers to adoption. Programs should ensure that alternative technologies become more attractive than those powered by natural gas. Natural gas phase outs for new builds (which some jurisdictions are already implementing) should be considered.

Efforts to scale up retrofits must focus on the integration of all the technologies and elements required to transform the existing building stock. In many cases technologies are already mature, available on the market, or available in other jurisdictions. But attention needs to be paid to combining them into 'whole of building solutions' that meet net-zero emissions standards while also improving the functionality of the building and the living and working experience of the occupants.

Targeted R&D and market development initiatives can be applied to specific technologies such as cold-climate heat pumps, prefabricated wall assemblies, digital devices for uses in virtual energy audits or building energy management systems. Research on hydrogen may open this up as a practical building heating solution – but this will depend on regional deployment.

To transform this system on the scale required it is essential to mobilize private financial capital, and a core objective should be to create institutional structures for a functioning private market for building retrofits. This includes development of common underwriting standards, aggregation of retrofit projects into larger financial portfolios, demonstrating investment opportunity to the private sector through de-risking, co-investing, information, and demonstration. A publicly supported investment vehicle can accelerate this process. Similarly, public sector procurement at all levels of government can drive the demand for net zero new builds and retrofits. Other salient issues include: expanding training and professional certifications in areas such as integrated design principles, and heat pump installation; regularly updating and harmonizing minimum energy performance standards for appliances and equipment; and introducing mandatory energy rating and disclosure policies (for energy and emissions) for commercial and residential buildings at the point of sale, rent, or lease.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Buildings**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Methane									
Natural gas	High. Mature technology	High. Very low price	No particular concerns. In general use	Yes. In general use	No – GHG emissions at point of use and during extraction	High for producers, pipeline companies and consumers	Uses existing infrastructure; indoor air quality issues	Already mature	Not a priority Fossil fuel
Renewable NG (biogas)	Early maturity.	Costs higher than natural gas. Limited sources of feedstocks	No particular concerns	Yes, similar to natural gas	Unlikely to be practical at scale. Lack of necessary feedstocks. Applicable in specific contexts. Could serve as back up for heat pumps	Interest from gas distribution companies and potential feedstock suppliers	Can use existing distribution infrastructure and appliances; air pollution not addressed	Some local opportunities	Low/medium Could play a part in a net zero economy but not at scale.
Synthetic NG (power from decarbonized sources, carbon from biomass or air capture)	Early research stage	Very high costs	No particular concerns	Yes, similar to natural gas	In principle, but requires cheap net zero hydrogen or renewables and biomass or air capture	Still at research phase	Can use existing infrastructure and appliances; air pollution not addressed	Remote for now	Low Could be part of net zero economy but a long trajectory
Electricity									
Base board or electric furnace	High, Mature technology	More expensive than gas, but widely used	No particular concerns	Yes, slower heating response time than gas	Yes, assuming net zero electricity supply	Not seen as particularly desirable because of cost concerns	Easy and well-known; low capital costs for baseboard heaters but inefficient	Limited as already mature technologies	Low but can be part of net zero buildings
Air and ground source heat pumps	High, but still improving	Good but high upfront costs	No particular concerns	Yes. Not applicable in all conditions. Less efficient in very low temperatures	Yes, assuming net zero electricity supply	Increasing interest from utilities as need to decarbonize become clearer	Significantly lowers utility bills and fuel costs. Reduces grid demand	Some potential	Very High Potentially significant part of net zero emission world.
Hydrogen									
Piped as a natural gas replacement	Pilot project phase	Depends on cheap low emission hydrogen	Some safety concerns.	Yes.	Yes. If hydrogen is made from decarbonized electricity such as renewables or from fossil sources with CCS and offsets.	Interest from existing natural gas distributors	Requires substantial adjustment to gas infrastructure. Requires new gas furnaces. Can support emergence of hydrogen economy	Transition to hydrogen economy for oil and gas. Potential life extension for gas distribution companies.	Medium to High Potentially part of net zero emission world.
Building generated power									
PV panels	High but new technologies can improve performance further	Dramatic cost reductions over previous decade. But not competitive for heating applications	No particular concerns. Positive public image	Yes. But power output not sufficient for heating in traditional buildings	Yes. Can be part of net zero buildings	Interest among some building firms	Net metering, sell back to grid; Can couple with storage	Industry well established. Some opportunities for local installers.	Medium. As part of integrated building solutions

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

ASSESSMENT TABLE: **Buildings**

* For explanation of criteria see Box B, page 22

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Building integrated PV	Technologies just emerging on the market	More expensive than traditional materials	No particular concerns	Yes. But variable, and power output not sufficient for heating in traditional buildings	Yes. As part of integrated energy solutions.	Still at demo stage. Intrigues some architects	Can reduce grid load and transmission losses. Contribute to system resilience.	Emerging materials opportunities: roofing, facades, windows etc	Medium As part of integrated building solutions
Micro wind turbines	Still be developed for integrated applications	Low – Long cost recovery	Birds and noise issues	Yes, but variable	Highest for AB, SK, and remote locations	Low at present.	Can couple with storage. Reduce grid load or congestion	Uncertain	Low, except for remote locations
Energy Efficiency									
Net-zero design (building shells and equipment)	Emerging but experience of deployment at scale lacking	Upfront cost higher. Already competitive over life cycle of building	No particular issues	Yes	When coupled with net-zero electricity	Some builders adopting as competitive advantage. Many wary of costs, lack skills. Consumers not convinced	Improved comfort: air quality, warmth, street noise, and lighting.	High, but need further skill training	High. Need to stop constructing buildings that will require retrofits for net zero
Retrofitting (building shells and equipment)	Specific technologies high. Approaches to mass retrofit emerging	Many investments repay in energy savings over time. Deep retrofits more challenging	No particular issues	Yes	When coupled with net-zero electricity	Becomes more attractive as carbon pricing and regulations rise.	Modern design; improved air quality and lighting	High for jobs creation, but need further skill training	High. Retrofits required to reduce net zero energy required.
Shared energy solutions									
District energy systems	Mature	High up front investment, but high efficiency and lower fuel costs	No particular issues with existing systems. Controversial to institute new schemes (finance, regulation)	Yes: can provide reliable heat and cooling	Yes, provided they run on net zero energy. Require minimum density of buildings.	Yes, especially for extending and upgrading existing systems.	Cost reduction, air pollution reductions.	Yes. Municipally owned systems or private companies.	Medium to high in contexts where it can be applied
Inter building energy transfers	Mature technologies can recover heat from industrial processes, server farms, sewage , etc.	Can be economic today, more so as carbon price and regulation increase	No particular issues	Yes. But systems must be designed for each specific application, matching source and recipient	Can be part of net zero building infrastructure	Yes, when building owners appreciate potential revenues, savings	Reduces energy consumption and costs, reduces pollution. Requires careful case by case design.	Yes. Underdeveloped in Canada and opportunities for engineering, design and construction	Medium to high in contexts where it can be applied

5.4 **Sector**: Oil and gas

Function	Fuel for transportation, power generation, space heating, industrial processes, and petro-chemicals
GHG emissions	193 $MtCO_2eq$ (2018) Canada's largest source of GHG emissions, 26% of national total
Options for decarbonization	Reduce production emissions from oil and gas sector to reach net zero; develop net-zero energy products derived from fossil sources; phase out fossil-based energy exploitation
Stage of transition	Emergence
Nature of the problem today	Entrenched political and financial interests, infrastructure lock-in, up-front capital costs, insufficient policy signals
Other systemic issues	Deep economic dependence on oil and gas industries, especially in producing regions; major problems with air and water pollution, contaminated sites; abandoned wells
Opportunities and concerns	Diversify economies of producing provinces away from traditional oil and gas production and associated boom/bust cycles; avoid stranding assets and further entrenching carbon lock in; leverage existing labour skills, industry resources, and infrastructure into new opportunities; develop, deploy, and export emission-reducing technologies
Priorities for action	Develop R&D and infrastructure for production of zero emission fuels (hydrogen or electricity) and geothermal energy, and material uses of bitumen. Dramatically improve energy efficiency and emission profile of existing oil and gas extraction. Scale back in-vestment in the sector not geared to an ultra low emission future
Longer-term issues	Phase out traditional oil and gas extraction; reclamation liabilities; developing net zero carbon offset markets
Indicators of progress	Sector emissions, net-zero by 2050 business plans with 2030 targets

For the last several decades, the oil and gas industry has fuelled economic growth in Canada. It remains a major economic driver: in 2018 the direct nominal contribution to Canada's GDP was 5.6% or $116.7 B. That year, it directly employed about 170,000 people or 0.9% of total employment. In 2018, the value of oil and gas domestic exports totalled $119B.[113] This represents 46% of Canadian gas production and 80% of Canadian oil production. Despite periodic downturns, this sector has been highly profitable for investors. However, recent trends indicate this sector's profitability is declining. In western Canada, transportation bottlenecks, high production costs, and declining access to capital markets, along with a shrinking social license (outside of oil and gas producing regions) have hit this sector hard. The collapse in international oil prices associated with the recent Covid-19 pandemic and the Saudi Arabia/ Russia price war provoked a full blow crisis for the sector and dependent provincial economies.

Compared to most industrial sectors, Canada's oil and gas industry has a high level of foreign ownership. In 2016, 44% or $284B of total oil and gas industry assets were controlled by foreign entities. This is 2.7 times the private sector average. In the oil sands, the level of foreign ownership is even higher, despite recent divestiture by eight international oil companies.[114]

NATURE OF THE PROBLEM

The oil and gas industry is the largest emissions source in the country. In 2018, production-related emissions from Canada's oil and gas sector were 193 Mt of CO_2eq, 26 per cent of Canada's total emissions.[115] This does not include the end-use emissions that come from burning oil and gas (approximately 80% of life-cycle emissions) which are included in sectors such as transportation and power generation or, in the case of oil and gas exports, transferred to foreign markets.[116] Growth in oil and gas production has predictably increased the sector's greenhouse gas emissions. Between 1990 and 2018, emissions from oil and gas production increased 193%, and per-barrel emissions-intensity increased 7%.[115] Despite increasing use of natural gas co-generation and some other efficiency measures, the expansion of energy intensive forms of oil and gas extraction (in-situ oil sands, hydraulic fracturing) and transmission (liquified natural gas) have more than offset efficiency gains. While combustion of gas results in lower greenhouse gas emissions than oil, fugitive methane emissions and processes like hydraulic fracturing for shale gas, and liquification, can substantially increase the emissions profile.

Beyond climate impacts, Canada's oil and gas industry has caused other environmental problems.[116] This includes multi-billion-dollar reclamation liabilities from abandoned well-sites, an estimated $130 billion of currently unaccounted liabilities associated with oil sands tailings ponds, and rehabilitating a highly fragmented landscape.

Dealing with Canada's oil and gas sector represents the single biggest emissions challenge for policymakers. It also represents an acute political and economic problem. Some regions remain heavily dependent on fossil fuel extraction while the country as a whole is increasingly determined to see action to address climate change. Even when oil prices recover from current record lows, Canadian producers (with a relatively high cost structure and a GHG intensive product) will remain under pressure.[204] Investment in more energy efficient extraction can help with costs and GHG reductions in the short term. But reconciling a continued future for the sector and decisive movement towards net zero GHG emissions is difficult.

NET-ZERO PATHWAYS

As presently constituted the oil and gas industry is incompatible with a net zero emission society. There are three potential elements to moving this sector forwards: (a) reducing production emissions to net zero while continuing to produce traditional fossil fuels; (b) exploiting hydrocarbons in novel ways by developing net-zero emission energy products; and (c) abandoning hydrocarbons for energy production and focusing on materials, and/or alternative energy resources. Elements of these approaches could be taken up by various segments of the industry and could be combined in different ways that vary over time.

OPTION 1: Produce oil and gas with net-zero production emissions.

The focus here would be a suite of technologies to shrink production emissions towards net-zero. Companies would use decarbonized energy for heat and power (applying CCS on any fossil sources), deploy alternative non-emitting oil sands extraction technologies, reduce fugitive methane emissions, and use battery-electric or fuel cell vehicles and equipment. Machine learning and artificial intelligence could increase process efficiencies and reduce emissions-intensity. Offsets would be required to address remaining emissions. Oil and gas products could be used domestically in ways consistent with a net zero GHG economy (i.e. when combined with further emissions capture and offsetting) or exported.

Although this pathway appears most directly aligned with the interests of existing producers, and initially could be pursued through incremental improvements to extraction and processing efficiencies, it faces many difficulties. Reducing production emissions to net zero will be expensive and technologically challenging, especially since an increasing share of Canada's oil comes from the oil sands. The availability of secure offsets (that are permanent and verifiable) at the desired scale (and price) is uncertain. And this in an international context where countries (with lower production costs) are competing to deliver product to stagnant or shrinking markets. Sixty percent of a barrel of Canadian crude goes towards gasoline and diesel, and these high-value products underpin the economics of the oil sector. As domestic and international demand is stripped away by electrification, the economic equation will look increasingly unfavorable.[77]

Nevertheless, in a context where there is significant doubt about the political will to drive decarbonization globally (and it is difficult to imagine Canada moving to net zero in advance of its peers), this strategy retains significant appeal for incumbents. Money can be made now, incremental adjustments to lower production GHG intensity can be made over coming years as policy becomes more stringent (or export customers impose GHG intensity requirements), and more fundamental change can be deferred.

OPTION 2: Develop alternative energy products that avoid GHG emissions.

Rather than seeing oil and gas as the core of their business, the industry could shift to producing zero emission fuels from hydrocarbons: hydrogen, or carriers derived from it, or perhaps electricity. Various resources and technologies could be employed, but ultimately in situ approaches could avoid greenhouse gas releases while producing net-zero energy carriers for export or domestic use. Technologies required for this pathway are immature, and hydrogen demand is currently insufficient to make this appealing.[117] Yet there is considerable international interest in hydrogen for difficult to decarbonize end-use sectors (such as cement, iron and steel, heavy freight), and for energy storage to facilitate higher grid penetration of wind and solar. Sustained investment over many years would be required to develop technologies and build demand for a hydrogen economy. Something like the long-term research and development and infrastructure investment programs deployed by the federal and Alberta government to develop the oil sands in the 1970s and 1980s could unlock this alternative.

OPTION 3: Wind down energy production from fossil sources and focus on materials production and/or renewable energy.

This involves a more dramatic reorientation of the sector away from fossil energy. A shift to renewable energy production could draw on some of the sector's expertise and assets. There are excellent solar and wind resources in Alberta and Saskatchewan, and significant untapped geothermal potential. Some major oil and gas companies are already diversifying into renewable energy assets. Another path would be to exploit fossil reserves for non-energy products. Waste from the legacy oil and gas industry could be transformed into a source of value creation. Lithium, an important input for battery manufacture, is a by-product of oil and gas drilling in certain reservoirs in Western Canada. Heavy metals (e.g., titanium) or rare earth minerals might be extracted from oil sands tailings. For bitumen producers, alternative products include activated carbon, vanadium (an input for batteries), carbon nanotubes, and carbon fibre. However, many of these production technologies are at an early stage of development, and the size of potential markets and Canada's comparative advantage are unclear. While there may be viable business models in the described activities, they would not rival the economic scale of the existing oil and gas industry.

It may be possible to weave a transformative pathway from elements of the three options described above, continuing to improve extraction efficiencies for oil and gas (to retain cost competitiveness and market access), while accelerating development of a hydrogen economy. Hydrogen supply would come first from natural gas with CCS (exploiting Alberta's current cost advantage) and demand would be built by moving to hydrogen fuel cells for heavy freight. Development of in situ hydrogen production would follow, and demand would expand to heavy industry, heating applications and export markets. Build-out of renewable capacity would allow production of 'green' hydrogen from electrolysis and grid storage applications. Such an approach could allow western Canada to remain a major energy supplier in a carbon constrained world. To have any likelihood of success it would require substantial and timely investments.

Navigating these options will pose acute challenges, with high economic and political stakes, for companies and governments. The mix and sequencing of elements will prove critical. Individual companies may well be able to balance different strands of activity to establish full net zero profiles, including for their 'scope three' (i.e. downstream) emissions. But that is different from saying the whole sector could successfully achieve such a transformation. Whatever transpires, regional economic diversification away from the traditional oil and gas economy will be important as will programs to retrain the workforce and aid communities.

CURRENT OBSTACLES

The first and greatest challenge is overcoming entrenched political and economic interests that support continuation of the current oil and gas development trajectory and the minimum incremental improvements required to maintain market access. Although the recent crisis has dented complacency, the reflex is to return to long established practices. However, there are reasons to believe that the window of opportunity is relatively short for the Canadian industry to reorient successfully towards a more transformative approach. Electrification of transportation is accelerating. Internationally governments are beginning to announce phase out dates for the sale of internal combustion vehicles. Implementation of supply-side policy measures to manage the decline of the oil and gas industry have begun to be imposed, including full or partial bans on exploration and production, abolition of investment subsidies, restrictions on public financing of oil and gas, and divestment by sovereign wealth and pension funds. Some international oil companies have already made relatively ambitious net-zero commitments — not just for production emissions, but for the full lifecycle of their businesses.[242] As accounting for carbon risk and fossil energy divestment gathers pace, pressure on Canadian firms will increase. The change of administration in the United States will accentuate these trends.

A second and interrelated challenge is the lock-in of existing oil and gas infrastructure. The half a trillion dollars of existing Canadian oil and gas assets was not built with net-zero emissions in mind. And further investment in traditional infrastructure (wells, pipelines, and so on) simply compounds the problem. Third, the up-front capital costs of shifting the trajectory, reducing emissions-intensity and developing net-zero emissions energy production, would be significant. And, since historically weak and inconsistent policy signals on decarbonization have been given to the oil and gas industry, charting a path forward for businesses and government is particularly challenging.

PRIORITIES FOR ACTION

If Canada's oil and gas sector is to be transformed into something other than a legacy business, which serves a declining customer base and leaves behind massive public liabilities (abandoned wells, tailing ponds and demoralized communities), then industry leaders and governments must set aside their defensive posture towards existing industry practices and begin to reconfigure for a net zero-emission world. This means accelerating measures to drive down existing production emissions (regulations, carbon pricing, abatement investment, etc.), and to explore the development of net-zero energy products and alternative activities. Multiple technical approaches to reduce emissions from conventional oil and gas and oil sands operations can be pursued — but policy frameworks, regulations, and investment must be set on a clear trajectory to net zero. Looking forward, it suggests the potential of an early and significant commitment to a hydrogen economy, with a research and development, infrastructure build out, and a demand-creation focus. Since incumbents are generally slow to embrace technologies that undercut existing business models care should be taken to prevent existing enterprises from monopolizing control over the new energy economy. While existing payers should be encouraged to diversify into clean energy production, there should be ample support for start ups and new entrants. This will need to be accompanied with policy supports for more general economic diversification in traditional oil and gas-producing regions, including support for training and net-zero compatible business development.

LONGER-TERM ISSUES

Over the longer-term managing the decline of traditional oil and gas extraction and charting a transformative path forward, will require careful adjustment to changes occurring across multiple sectors (oil and gas production, emergence of a hydrogen economy, development of CCS and suitable offset mechanisms, the pace of personal vehicle electrification and uptake of fuel cell technology for heavy transport, and so on). To say navigating such an uncertain and turbulent terrain will be a challenge is an understatement.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

ASSESSMENT TABLE: **Oil and gas**

* For explanation of criteria see Box B, page 22

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Oil and gas production (non-oilsands)									
Methane emission reduction	Well developed technologies to reduce fugitive emissions	Depends on context	High	High	Only as part of an integrated strategy to get to net zero.	To industry incumbents when faced with regulatory or cost pressures	Adds costs for abatement but may generate revenue through reduced methane wastage. Reduces GHG intensity of product (foreign market access)	Growing market for specialized oil and gas equipment	Medium. Necessary as long as fossil fuel extraction continues.
Machinery equipment and vehicles	Emerging. Electric or hydrogen fuel cell	Varies but more expensive than diesel	No particular problems	Yes.	Only as part of an integrated strategy to get to net zero.	To industry incumbents when faced with regulatory or cost pressures	Reduction of air pollution	For equipment or vehicle manufacturers	Low to medium Important as long as fossil fuel extraction continues
Oilsands production									
Equipment and vehicles	Developed or emerging	Varies but more expensive than diesel	No particular problems. But increasing public concern over oil sands	Yes. But limited compared to overall emissions	Only as part of an integrated strategy to get to net zero	To industry incumbents when faced with regulatory or cost pressures	Reduction of air pollution	For equipment or vehicle manufacturers	Medium. (small part of overall GHG production footprint)
Low carbon electricity for SAGD or other approaches	Multiple low carbon options including electricity from low carbon grid, renewables, small modular nuclear reactors.	Much more expensive than natural gas now. Might make sense faced with tight regulations and high carbon price	Varies by generation technology (see power table Section 5.1)	Yes, depending on circumstances	Only as part of an integrated strategy to get to net zero.	Depends on cost, regulatory environment, oil market conditions.	Potential energy and cost savings. Reduced air pollution. Danger of further stranded assets as oil demand declines.	For suppliers of alternative energy technologies	Low to medium. Option while oil extraction continues
Alternative extraction approaches	Multiple possibilities at R&D and demo stage including solvents and radio frequency heating	Expensive but potential cost savings when mature from reduced energy use	Unknown	Yes, in principle but not tested at scale	Only as part of an integrated strategy to get to net zero. Data on performance closely held by companies so impossible to verify real emission reduction potential	Yes, oil producers. Depends on costs, regulatory environment, oil market conditions.	Potential energy and cost savings. Reduced air pollution.	For suppliers of alternative extraction technologies	Low to medium. Option while oil production continues
Artificial intelligence & machine learning									
	Technology still emerging and oil and gas applications under development	Unclear. Depends on context	No particular problems	Yes, in principle	Only as a small part of an integrated strategy to reduce emissions	Yes. Current industry enthusiasm to reduce costs and raise efficiencies	Increases recovery rates and reduces cost. Could threaten some jobs	Could creates demand for skills that can be transferred to other sectors	Low priority for substantial de-carbonization

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Oil and gas**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Carbon capture and storage (CCS) across the industry									
For energy production, bitumen upgrading, hydrogen production, refining, etc.	At large demo stage	Depends on application, more development required to reduce costs	No organized opposition today, some concerns about leakage	Yes. But adds costs and complexity to operations	Depends on application. Must be supplemented with offsets to reach net zero.	Yes, in appropriate context. Can be applied to existing facilities	Creates a feedstock of CO_2 for storage or industrial use	Potential to be linked to hydrogen economy development	High. Potentially useful in multiple contexts.
Negative emissions technologies									
To offset residual emissions. Direct air capture, afforestation, agricultural practices, BEECs, etc.	Technologies at different stages of development	Highly variable: tree planting cheap, air capture expensive, etc.	No organized opposition	In principle. But many uncertainties about permanence, effectiveness, costs, scalability	In principle. But questions about permanence, and scale available to offset residual emissions from fossil fuel production and use - because of offset required elsewhere in the economy and eventual need shift entire economy to net negative.	Some offsets in use to meet existing carbon pricing schemes	Allows continues production of fossil fuels with the costs and benefits this entails	Potentially, if adopted at scale	Low to medium (varies with approach). R&D and demos to gain experience and understanding
Hydrogen production (as an alternative energy carrier)									
Steam-methane reforming (NG feedstock) **without CCS**	Well established technology	Economic technology producing hydrogen for many industries	Some concerns about hydrogen safety	Yes	Not net zero. Only as a transitory path of low emission hydrogen production	Increasing interest in hydrogen across multiple sectors	Produces abundant GHGs.	Transition to hydrogen economy	Not net zero compatible
Steam-methane reforming (NG feedstock) **with CCS**	Hydrogen established. Hydrogen production with CCS: large scale demos already underway	Currently expensive	Some concerns about hydrogen safety	Yes	Potentially net zero if offsets for NG extraction and transmission	Yes	Fossil energy producers as hydrogen emerges as a viable energy carrier	Transition to a hydrogen economy	Medium high To accelerate low carbon hydrogen deployment
In-situ gas wells	Still at experimental stage	Unknown: too early in development	Some concerns about hydrogen safety	In principle	Potentially. With sequestration of emissions and offsets to mop up residuals	Not appealing while gas production possible, and hydrogen demand undeveloped	Maintain revenue stream from mature oil and gas reservoirs. Uses existing pipeline infrastructure Reduces air pollution	Energy production/ exports in a decarbonizing world.	Medium high Potential net zero hydrogen production
In-situ oil sands	Still at experimental stage	Unknown: too early in development	Some concerns about hydrogen safety	In principle	Potentially. With sequestration of emissions and offsets to mop up residuals	Not appealing while oil production possible and hydrogen demand undeveloped	Maintains revenue stream from bitumen resource. Reduces air and water pollution	Energy production/ exports in a decarbonizing world.	Medium high Potential net zero hydrogen production

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Oil and gas**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Geothermal Electricity									
Utility-scale power generation	Demonstration scale in Canadian context	Not cost competitive today	No problems today. For some technologies local concern over fracking and seismic activity	Yes, in principle. Continuous baseload power	Yes	No strong constituency yet, but emerging	Geographic overlap between geothermal resources and oil and gas areas	Some, helps transition away from oil and gas extraction	High as alternative development trajectory in Alberta
Non-combustive uses for bitumen									
Activated carbon, vanadium, carbon nanotubes, carbon fibre	Varies according to materials	Not commercially attractive today. Longer term prospects unclear	Concerns remain re: bitumen extraction (tailings, emissions, liabilities, land disturbance)	High	Possible if extraction and processing emissions are avoided, captured and/or offset	Yes	Increasing demand for carbon nanotubes/fibre and vanadium as decarbonization deepens	Possibly but cost unclear and many competing sources	Medium. Possible diversification strategy for Alberta
Lithium									
Direct extraction from oilfield wastewater	Under development	Expensive today (no commercial operations)	No particular problems	Yes, in principle	Yes with net zero extraction	Potentially, if profitable	Growing demand for lithium, does not require mining	Depends on growth of demand, and there are many potential competing sources.	Low. Possible diversification strategy for Alberta.

5.5 **Sector:** Mining

Function	Extraction of minerals used for multiple purposes across all sectors
GHG emissions	8 $MtCO_2eq$ (2018), 1% of total national emissions
Options for decarbonization	Electrification, advances in extraction and processing technologies, recycling and recovery, managed decline of coal
Stage of transition	Emergence/diffusion (metal recycling, improved extraction and processing technologies); Early diffusion (electric equipment, onsite renewable energy production and storage)
Nature of the problem today	Legacy infrastructure, high up-front costs, lack of regulatory framework (metal recycling and recovery)
Other systemic issues	Pollution; worker health and safety; remediation of abandoned sites; relations with Indigenous peoples
Strategic opportunities and concerns	Potential to reduce operational costs, improve air quality and worker health, and create new revenue streams (metal recycling and recovery). Design, build and test new electric mining technologies in Canadian labs and mines, export technology. Markets for minerals critical to a low carbon transition (for example, batteries). Indigenous land claims and opportunities for partnership. Competitiveness issues: need for international collaboration
Priorities for action	Incentivize use of electric mining equipment, and on-site renewable energy production and storage; regulatory framework and funding of pilots to encourage metal recovery/recycling
Longer-term issues	Lifecycle management of batteries, mine site reclamation, production of metallurgical coal
Indicators of progress	Proportion of mining equipment that is electric or fuel cell; volume and value of recycled metals.

CURRENT STATUS

Canada has a significant and well-established mining sector with over 200 active mines and 6,500 quarries.[183] The direct contribution of the mining sector to Canada's 2018 GDP was $72.4B or 3.5%. The sector directly employs about 180,000 (in extraction, services, and primary manufacturing).[118] These numbers do not include oil sands operations. Mining is a major source of export earnings. In 2018, the total value of Canada's domestic mineral exports was $104B.[183] The top five mineral exports that year were gold ($17.3B), iron and steel ($16.5B), aluminum ($13.0B), metallurgical coal ($7.9B), and copper ($7.6B).

Many Canadian mining companies operate abroad. Of the sector's $260B in assets (2017), 65% were located outside the country. In 2019, the Toronto Stock Exchange was the top exchange in the world for global mining equity financing. Compared to most industrial sectors, Canada's mining industry has a moderately high level of foreign ownership. In 2016, 27% of total mining industry assets were controlled by foreign entities, 1.6 times the private sector average.[210]

NATURE OF THE PROBLEM TODAY

The main challenge to decarbonizing this sector is the remote location of most mines, sunk investments in existing mining infrastructure, high capital costs for new equipment (for example, electric vehicles, processing equipment, net zero energy supplies) and competitiveness concerns in this globally integrated industry. In 2018, Canada's mining sector emitted 8Mt of CO_2eq or approximately 1 per cent of Canada's total emissions. At the mine site, stationary emissions come from electricity generation (needed for ventilation, lighting, ore processing, etc.).[30] Diesel trucks are the largest source of mobile emissions. Since 1990, emissions have remained flat while the sector has grown significantly. Many remote mines rely on expensive and polluting diesel generators to power operations. Mining companies face increasing environmental and economic pressures from local and Indigenous communities and are subject to more stringent regulation. Unsettled Indigenous land claims in some regions complicate mine development. It is now common practice for mining companies to sign impact benefit agreements with local Indigenous communities. These are intended to share economic benefits and minimize potential harms.

The mining sector in Canada has begun to re-position itself as a supplier of metals and minerals for a low carbon economy. As decarbonization accelerates, demand for key materials for batteries, such as lithium, cobalt, nickel, and copper, is increasing. On the other hand, demand for thermal coal will fall as Canada phases out coal-fired generation. Metallurgical coal (which makes up 97% of Canada's coal exports) will continue to be needed by the steel industry until alternative foundry technologies are developed, and diffuse internationally, over coming decades.[119]

NET-ZERO PATHWAYS

The fundamental approach to achieving net-zero emissions in mining is the modernization of extraction and processing techniques (for example for comminution – crushing and grinding of ore) and electrification of mine operations. Promotion of resource efficiency in mineral consuming industries, reuse, and recycling (embracing the circular economy) provides a complementary track. Given the established global leadership of Canada's mining sector, and existing public and private sector activities currently underway, Canada is well-positioned to lead on both paths.

Electrify everything. Energy is often the largest operational cost for mines. Many of Canada's remote mines are off-grid and rely on diesel for power generation and operational equipment. For underground mines this means additional costs for ventilation and increased health risks for workers from air and noise pollution. Mine electrification can reduce operational costs. Electric (or hydrogen fuel-cell) mining equipment eliminates the need for diesel, improves air quality in underground mines, eliminates tailpipe emissions, and reduces ventilation costs and noise. Newmont Goldcorp's Borden gold mine in Ontario, which opened in 2018, is the first all electric underground mine in Canada.[182] Major equipment manufacturers like Komatsu and Caterpillar as well as several Canadian firms (e.g., Maclean Engineering) already sell battery electric mining equipment. Hydrogen fuel cell electric technology is currently under development for mining applications, providing torque, size and weight advantages over batteries. But this equipment is not yet in commercial production. In March 2020, the federal government announced that mining companies can write off 100% of the purchase cost for zero-emission vehicles.

On-site wind and solar-PV power generation, when combined with energy storage technologies, can reduce carbon emissions for off-grid mine sites, or those connected to emission-intensive electricity grids. Glencore's Raglan mine in Quebec has two wind turbines and an energy storage system, which includes a small hydrogen generator.[181] Between 2014 and 2019, the mine's new power system displaced 10 million litres of diesel fuel. Small modular nuclear reactors have also been proposed as a longer-term option for power generation at mines, but the technology remains far from market and it is uncertain how cost, safety, and security concerns will be overcome.

Transform extraction and processing technologies. Achieving full electrification will require major advances in mineral processing technologies to allow continuous operations, reduce material brought to the surface, increase sorting efficiency, upgrading, and so on. Such platform improvements could dramatically increase energy efficiency, reduce water use and tailing discharges, raising operational efficiencies. Modernizing mining processes (which in some respects have remained remarkably stable) to eliminate inherent energy efficiencies can also help address the long-standing problem of declining ore quality, where more material must be processed to extract a given quantity of mineral. It will require continued research and development and significant capital expenditures.

Recycle and reduce usage. Greater demand for metals and minerals needed to decarbonize the economy could increase the cumulative environmental impacts of mining. Encouraging materials efficiencies in industries that consume mine products and promoting recycling (keeping materials in circulation and postponing final waste disposal) can limit primary extraction. This potentially decouples economic growth from increasing natural resource consumption and complements electrification. Recycling is well developed for some metals (steel, aluminum) but immature for others. The global e-waste recycling market is expected to increase six-fold by 2050, providing a valuable source of metals such as gold, copper, and aluminium. This could create new economic opportunities.

These approaches to net-zero emissions face significant obstacles. The high up-front capital costs of non-diesel power generation and electric or fuel cell trucks and equipment, along with the sunk equipment costs associated with existing infrastructure that require significant upgrades, make decarbonization financially unappealing for many mining companies. Recycling initiatives can appear to threaten primary producers. Canada currently lacks a policy and regulatory framework to incentivize metal recovery and recycling.

Although absolute production emissions are not high, coal mining poses a distinct challenge. While thermal coal extraction is expected to decline as coal is eliminated from the power sector, demand for metallurgical coal will remain for some time. Fugitive methane emissions will therefore require offset provision. And policies to ease the burden for impacted workers and communities will be required.

PRIORITIES FOR ACTION

Transition in this sector can be accelerated by incentives to lower capital costs for electric mining equipment and on-site renewable production and storage, and measures to promote retirement of diesel generators and mining equipment. These could be linked to industrial policy measures **(a)** to support Canadian companies that can provide net zero mining technologies and power supplies, and **(b)** to expand mining of materials required for society-wide electrification. A regulatory framework for metal recycling and recovery would lower uncertainty and speed market development. Some mining companies have already begun to process recycled materials at their smelters and refineries, and government support for pilot or demonstration projects could help.

Several longer-term issues await attention. The increased use of batteries and fuel cells, both at the mine site and by consumers, creates concerns about end-of-life disposal. Improved lifecycle management will be needed to minimize the potentially toxic legacy of these zero-GHG emission technologies. Increased demand for metals and minerals may exacerbate existing reclamation liabilities for the sector. Measures to address remaining metallurgical coal production will ultimately be required

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Mining**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Electric mining equipment	Reasonably mature. OEMs have begun to sell battery electric equipment. Hydrogen fuel cell mining equipment under development	High - higher capital costs offset by lower operational costs	No particular problems	Yes	Yes. Essential	Yes because of maturity and potentially favorable economics	Reduced air pollution. Could be combined with autonomous and connected vehicle technology but requires new labour skills at mine site. Benefits from safety,	High - some mining equipment is already assembled in Canada. Opportunities for research, design, engineering, and assembly in Canada	Very high
On-site renewable energy generation and storage	Early mature and continuously improving	Can be good but site-specific	No particular problems	Yes	Yes	Yes when site circumstances are appropriate	Reduces reliance on diesel generators, improves reliability of power supplies, requires new labour skills at mine site, reduces local air pollution	High, given the current low adoption of these technologies and the potential for domestic suppliers	Very high
Small modular nuclear reactors (SMRs)	Low - SMRs are pre-commercial	Too early to tell what costs will be	Public concerns around safety and waste disposal	Yes. Scaling of plant to demand will be critical	Yes in principle. For full net zero requires decarbonized production chain	Strong support from the nuclear industry	Can provide emission free heat and power to local communities. Requires new labour skills at mine site. Multiple issues: long term waste storage, risk of accident, security, decommissioning costs. Complicates site remediation	Yes, given existing nuclear industry	Low to Medium. Technology not yet available
Transformation of extraction and processing technologies	Different degrees of maturity	Dependent on specific technology and process	No particular concerns	In principle	Yes: contributes by lowering requirements for decarbonized energy production and storage	From operators when cost effective	Reduces operational costs. Can reduce water use, tailings	High. Innovations can be marketed for global applications	Medium/high Essential for electrification
Metal recycling and recovery technologies	Many already mature	Dependent on specific materials and technology	No particular concerns	In principle	Can contribute. to net zero. Requires decarbonised energy supply	Potentially	Reduces operational costs, creates additional revenue stream	Some, market innovations for global applications	Medium Complements other approaches
Materials efficiencies in consumer sectors	Varied	Depends on application	No particular concerns	In principle	Can contribute, by reducing need for primary or recycled materials. But spread across many economic sectors and difficult to secure	Appealing to end use industries, not necessarily primary producers	Reduces material throughput, air and water pollution, biodiversity pressures	Potentially, but spread across many industries	Low to Medium Complements other approaches

5.6 **Sector**: Cement

Function	A binding agent in concrete: a mix of cement, aggregates and water that is a basic construction material
GHG emissions	11Mt of CO2eq (Process emissions about 60%, energy use emissions about 30%, with the remainder from transport and operations). Approximately 1.5% of Canadian emissions.
Options for decarbonization	Switch from fossil fuel to net zero energy supply, carbon capture and storage, low carbon cement mixes and alternative cement chemistries, reduction in demand/efficient use
Stage of transition	Early emergence
Current obstacles:	Decarbonisation technologies are capital intensive, some are immature, while others face regulatory policy barriers. Weak demand for low carbon cement and high building sector sensitivity to material prices; cumbersome codes and standards processes slow to adopt innovations; competitiveness concerns
Economic/social opportunities:	Job creation while developing and implementing new technologies, reduction in air pollution and associated health risks; climate adaptation/resilience applications
Industrial policy/competitiveness	Cement production in Canada is dominated by multinational parent companies; international collaboration can accelerate decarbonization
Priorities for action	Public investment in demonstration and commercial applications of viable low carbon cement technologies; government procurement of low carbon cement and support for material-efficient design; movement to performance based codes and standards; research and development on novel technologies.
Longer-term issues	Alternative cement chemistries; alternative building materials
Indicators of progress	Per cent change in GHG emissions from cement manufacture; market penetration of low carbon cement

Cement serves as a binder in concrete, a basic material used for all types of construction, including commercial and industrial buildings, housing, roads, schools, hospitals, dams, and ports. In Canada, a cubic meter of concrete per capita is used in construction each year.[178]

The cement industry directly employs about 2000 people in Canada, and in 2014, produced over 13 million tonnes of cement, with a dollar value of $1.64 billion.[163] There are 17 cement manufacturing plants in Canada (16 integrated and 1 grinding plant).[164] Cement production is concentrated in central Canada (Ontario 50% and Quebec 17%), with exports going to the United States.[165]

NATURE OF THE PROBLEM

The cement industry is energy, material, and carbon intensive. Most energy is consumed by the kiln process while about 10% is used in activities related to fuel and raw material preparation, grinding of clinker and the blending of materials to prepare the finished product. In 2009, energy inputs for cement production in Canada came from coal and petroleum coke products (82%), electricity (13%) natural gas, liquid petroleum products and waste oil products (4%) and tire-derived fuels and other alternative energy sources (2%).[166] Over the past decade there has been movement towards gas and alternative fuels.

In 2017, the cement industry emitted 11.27 Mt of CO_2eq — an 8.4% increase from 2005 levels.[167] This represents approximately 14% of heavy industry emissions and 1.5% of Canada's total emissions. Of these, 6.75 Mt CO_2 (60%) - are process emissions associated with clinker production. The majority of the rest were from fuel used to produce high temperatures required in the kiln.

Cement production is capital intensive, demanding a substantial upfront investment in plant with a long potential lifetime. Five companies currently dominate production in Canada. The Canadian industry, largely owned by multinationals, faces competition in global markets, particularly in the U.S.[168]

NET ZERO PATHWAYS

A variety of approaches will be required to shift cement production towards net zero. Although incremental emission reductions can be achieved by energy and operational efficiencies, more fundamental change will be required to address energy-related and process emissions.[172] Key elements than can contribute to such a transformation include:

Net zero energy. Replace fossil fuels burned in kilns to provide heat with renewable (or other net zero) energy. This could be achieved by combustion of biomass and/or waste, electric heating, or hydrogen.[81] Waste and biomass have already been used as partial substitutes for fossil fuels within the sector, however provincial policy barriers have contributed to Canadian facilities lagging international best practice. To date such fuels have included waste wood, paper, textiles, plastics, tires, asphalt shingles, and so on. Moving to 100% alternative fuels in kilns poses technical challenges. There are concerns about achieving a consistent fuel mix, the availability of fuel supply, as well as with the carbon footprint of substitute fuels, and air pollution. Switching to electricity would be possible but has not been tested at industrial scale. It would entail substantial kiln redesign. Hydrogen is an alternative but would again require kiln redesign, as well as reliable supplies of inexpensive low carbon hydrogen.[81]

Low carbon cements. Reducing the proportion of (energy and process emissions intensive) clinker in the final cement mix by adding additional cementitious materials can significantly reduce emissions. Blast furnace slag and coal fly ash are the most common such materials used today, although supplies are being disrupted as decarbonization in other sectors proceeds. New cementitious materials are being actively researched. Cements incorporating local calcined clays and limestone with clinker and gypsum can reduce process emissions by perhaps 40%.[171] More fundamentally, novel cement chemistries could replace traditional limestone-derived clinker. A number of such chemistries, with varying emission intensities, are currently being explored. One option is alkali/geo-polymer-based-cement, which could reduce emissions by 70% as compared to conventional clinkers and utilises minerals which are widely available.[81] Magnesium silicate or ultramafic cements could eliminate emissions entirely (or even achieve carbon negative results), but these remain in the early development phase and material availability may limit their potential contribution.

Carbon capture, utilization and storage. Capture of CO_2 from process emissions, and perhaps also from fuel combustion, could play an important role in the solution mix.[170,171] Captured CO_2 would be sent underground for sequestration or used in other industrial processes. Technology to inject CO_2 into wet concrete, strengthening the building material and/or sequestering carbon in the resultant structure, is already being deployed on a small scale. It may also be possible to accelerate the process by which concrete naturally absorbs CO_2 as it ages (for example, allowing rubblized cement to remain exposed to air or exposing it to concentrated CO_2 streams) thus reducing the lifecycle GHG emissions of cement and concrete.

Reducing demand. Cement use can be minimized by improving the design of structures to require less new cement and concrete, and to employ more recycled construction material. Concrete can also be replaced by other materials that have lower emissions profiles. Emissions from timber construction can be significantly less than concrete in similar applications.[179] New forms of wood construction, including cross-laminated timber, could compete with concrete in low to mid-rise construction, but have yet to be widely adopted. Research is ongoing into a variety of net zero (or in some case net negative) building technologies.

Cost remains a key challenge for deep decarbonization, particularly for a low-margin product such as cement. Indeed, cement may be the costliest 'difficult to decarbonize' industrial sector to address.[171] Some have suggested a potential doubling of cost (equivalent to a 30% increase in the cost of concrete). But experience with initial cost estimates for meeting other environmental objectives, and possibilities for significant technological advance, suggest this may be an overstatement.

PRIORITIES FOR ACTION

There is no single path to decarbonize the cement industry. The demand for low carbon cement is currently low, and the adoption of lower carbon cements may require adjustments in construction techniques and building codes. For example, alternate cement compositions may have different setting times or structural characteristics.[180]

Decarbonizing this sector is critical and can complement other sectoral transitions in buildings, heavy industry, and roll out of CCS technologies and the hydrogen economy.

Governments should encourage R&D, and support large scale demonstration, and commercial application of technologies that can address energy-related and process emissions — potentially including electric, hydrogen and biofuel heating, CCS applications and novel cement chemistries. Carbon pricing, performance-focused building codes and public procurement can advance market penetration of cement with a lower carbon footprint. Measures can be introduced to improve building design to reduce material usage, discourage landfill of construction waste and encourage recycling of building materials. As the cement industry is composed of a small number of large international firms, international coordination can accelerate change.

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Cement**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Alternative fuels									
Biomass and/or waste	Already being applied at scale. But challenges moving to 100% alternative fuels (eg: lower calorific value of biofuels as compared to fossil fuels).	Depends on fuel sources Today less expensive than contemplating electrification or hydrogen but more expensive than traditional fuels	Could be concerns over air pollution and waste incineration and transport of solid fuel	Yes in principle.	Yes, for energy emissions if biomass is sustainably harvested. Some fuels from waste emit GHGs (eg tires, asphalt shingles, etc), so requires full lifecycle analysis to verify net zero emission credentials of waste fuels. Must be combined with approach to manage process emissions	Currently easiest option to substitute for fossil fuels in kiln heating	Can use local biomass or waste streams Competing uses of biomass in net zero economy. Air emissions	Some for local enterprises producing biomass or managing waste streams	Medium/High For further R&D and pilots
Electrification of heat	Several alternatives at research and development stage. Preparations underway for pilot using plasma technology	Depends on availability of cheap low carbon electricity.	No particular issues (but related to source of low carbon electricity)	In principle high	Assuming decarbonized electricity, high for energy emissions. But must be combined with approach to manage process emissions	Interest where low carbon electricity is available and strong carbon commitments.	No air pollution. Large electricity requirement, so there may be competing uses for low carbon electricity.	Particularly for firms that secure breakthrough technology.	Medium high. For further R&D and pilots. Especially in areas with plentiful decarbonized electricity
Hydrogen	At research and development stage. Kiln redesign for 100% hydrogen. Some pilots being explored	Depends on availability of cheap low carbon hydrogen	No particular issues	Yes, in principle	High for energy emissions. But must be combined with approach to manage process emissions	Interest where hydrogen sources may become available	No air pollution	Particularly for firms that capture breakthrough technology.	High. Could be integrated into a broader hydrogen economy
Hybrid approaches	At research and development stage. Some pilots being planned	Difficult to determine. Uses some mix of biomass and/or electricity and/or hydrogen. Could allow adjustment to lowest cost fuel mix	No particular issues.	Yes, in principle	Yes, in principle. But must be combined with approach to manage process emissions		Depends on hybrid mix	Depends on hybrid mix	Medium

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Cement**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Low carbon cements									
Substitution of clinker	Varies according to materials to be substituted to reduce clinker proportion.	Costs range considerably	No particular issues	Yes, in some cases strengthens or otherwise improves product	Possible but limited as clinker emissions cannot be eliminated while cement chemistry remains the same. Process emissions must be combined with energy emissions reductions.	Medium	Depends on the alternative used. In case of using waste materials, industrial waste that goes to landfill can be reduced	Medium	Medium
Changing cement chemistries	Alternative chemistries at different levels of development	Vary with chemistry, availability of feedstocks and still hard to determine	No particular issues	Yes in principle	Yes, but depends on new which new chemistry is adopted. Energy requirements may vary	Not yet clear	Not yet clear, depends on alternative	Not yet clear, depends on alternative	Medium/High Important and could substantially decarbonize sector, but long R&D road ahead.
Carbon capture, utilization and storage									
	Feasibility study to equip an Edmonton plant is ongoing. Multiple pilots being pursued in US and Europe	With carbon pricing CCS potentially economic but high upfront capital costs	No particular issues	Yes, for both energy and process emissions. Could be coupled with part biomass combustion to remove need for external offsets (as capture rate is less than 100%)	Most analysts assume an essential element to get cement to net zero. Can capture 90% of process emissions and possibly other emissions. Requires suitable storage sites (excellent in Western Canada)	Yes, as it allows continued use of existing cement chemistries	Captured CO2 can be injected into concrete to strengthen it. Other uses possible. But scale of industry suggests underground sequestration will be required	Can lik to broader applications across economy including hydrogen production	High

5.7 **Sector:** Agriculture and agri-food

Function	Provides food, fiber, and fuel. A foundation for health and prosperity.
GHG emissions	For agriculture: 10% of Canadian emissions (2% from energy use; 8% from agricultural practices). The full sector has additional emissions from input production and food processing, manufacture, and transport.
Options for decarbonization	Alternative cropping and soil management practices; low emission fertilisers, precision application. For animal agriculture: improved feeds and genomics; better manure management. Reduce meat and dairy in diets, with greater reliance on plant-based foods, or alternative proteins. Replace on farm fossil fuel use with electricity, biofuels, and hydrogen.
Stage of transition	Early emergence
Nature of the problem today	Complexity of addressing emissions from a geographically dispersed and heterogeneous sector, where most emissions result from the intersection of agricultural practices and biological processes. Heavy reliance on high input agriculture. Market, regulatory frameworks, and government programs that do not incentivize sustainable agriculture and land use.
Other systemic issues	Soil health, biodiversity loss, water pollution, food waste. Heath concerns: sugar, salt, highly processed foods, and proportion of animal protein in most diets. Concentration of ownership of agri-food sector. Migrant labour dependence.
Opportunities and concerns	Supporting rural communities. Building Canada's reputation as a trusted food brand, with a growing role in international sustainable food markets. Climate impacts on agriculture: negative (drought, flooding, more extreme weather, vulnerability to pests and disease) and positive (longer and warmer growing seasons).
Priorities for action	Reform support programs to encourage improved agroecological practices. Align market actors (finance, processors, input manufacturers) to incentivise more sustainable value chains. Research, trials and promotion of alternative crop regimes and technologies to reduce nitrogen fertiliser inputs. Improve management of manure and ruminant diets. Research animal genomics, diet, inhibitors, to reduce enteric emissions. Encourage alternative proteins.
Longer-term issues	Address impacts of climate change on agricultural production. Explore soil and land-use based opportunities for large scale carbon sequestration. Develop agricultural production regimes that are more attuned to agroecological principles.
Indicators of progress	Fossil fuels as proportion of on-farm energy use. Reductions in nitrogen fertiliser application and reduced eutrophication. Increases in soil organic matter and soil organic carbon. Lifecycle GHG emissions per unit of protein.

Canada is a major agri-food producer and exporter, with the sector accounting for about 11% of the country's GDP.[230] Field crops are dominated by wheat, canola, barley, soybeans, and lentils, while beef and dairy, pork and chicken are the major livestock products. About half of agricultural production is exported (and half of that goes to the United States), with most of the remainder going to the food processing industries. In 2016, Canada had a trade surplus of $13.5 billion in primary agriculture, but a trade deficit of $1.9 billion in processed agri-food products.

Approximately 2.3 million people are employed in the agri-food industry. Primary agriculture makes up only 12% of this total, with the rest involved with inputs and services (3%), food and beverage processing (12%), retail and wholesale (28%) and the food service industry (44%).[226] In 2016 there were approximately 190,000 farms in Canada.[227] This number has declined steadily over time, while average farm size has increased.[229] The largest operations produce the bulk of the output. Thus 8% of farms with gross receipts over a million dollars generated 60% of national farm revenue in 2016, while 56% of farms with receipts of less than $100,000 generated just 5% of the total.[225]

Corporate concentration is significant. This is particularly true for input supply (seeds, fertiliser, herbicides, pesticides, and equipment), food processing (meat packing, manufacture) and retail (supermarkets).[136] In 2018 the four largest food retailers had nearly 80% of the market share.

In contrast to other systems of social provisioning (for example, transport or buildings) agriculture relies more directly on natural cycles and ecological systems, and is dependent on local soil conditions, rainfall, and climate. Climate change is already impacting the sector and larger impacts are expected in the future.

Although agricultural support programs in Canada are less generous than in some OECD countries, they still contribute around a third of farm operator income. Crop insurance payouts are the largest component of federal spending on agriculture. Because of its export orientation, the sector is highly exposed to disruption in international trade patterns from disputes or political tension.

Two major technological revolutions are impacting the sector. Digital technologies (sensors, GPS, drones and satellites, robotics, 3D printing, blockchain, large data sets, machine learning and artificial intelligence) are changing the ways crops and livestock are managed.[149] While advances in biotechnology (including trans-genetics, genome editing, and marker-assisted selection) are permitting new crop development, novel pest control strategies, and the emergence of precision fermentation and cultured meat.[231,232,233]

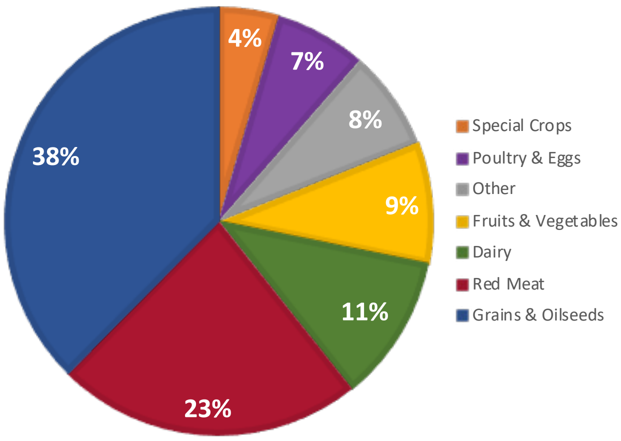


Figure 14-A. Farm market receipts, 2017, billions $

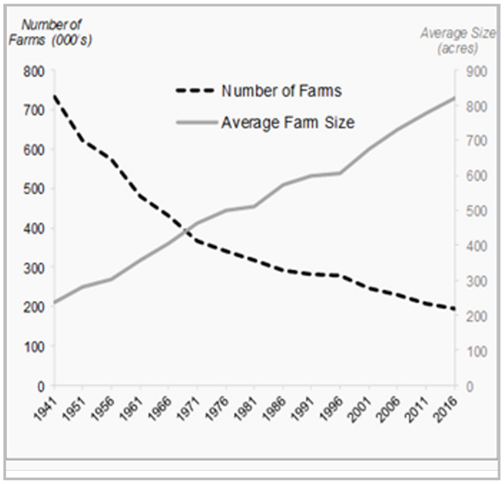


Figure 14-B. Number and size of farms 1941-2016

Figures 14. Canada's Agri-Food sector

Source: Agriculture and Agri-Food Canada, 2019.[120]

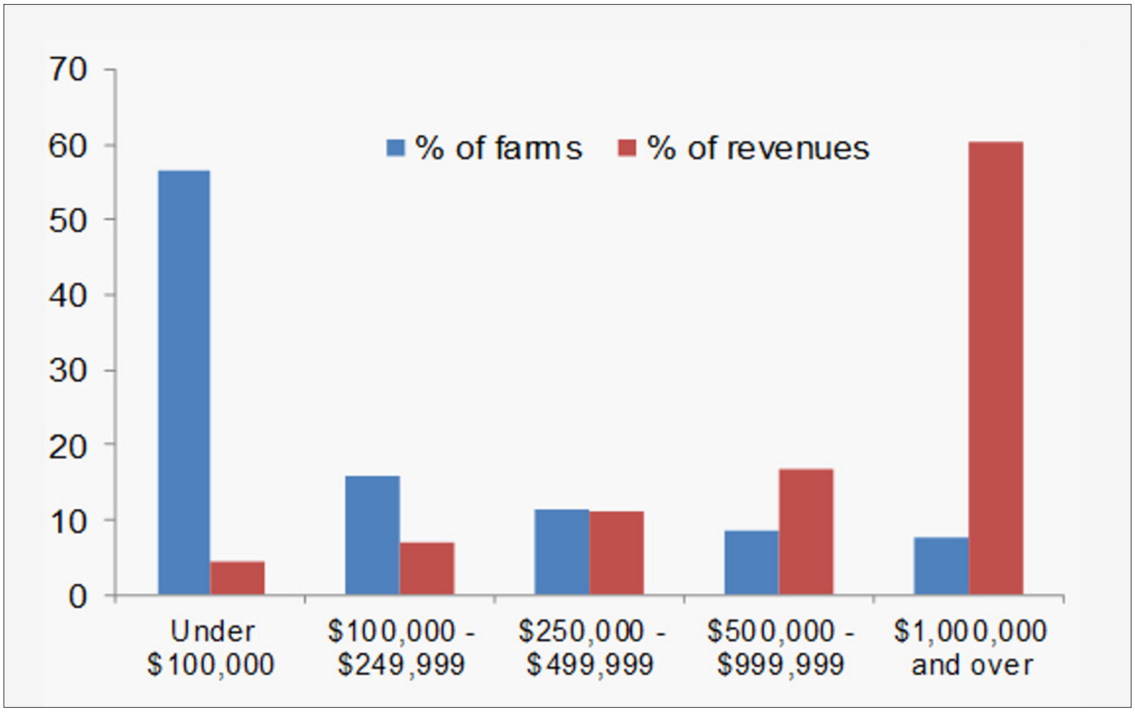


Figure 14-C. Distribution of farms and gross farm receipts, 2016

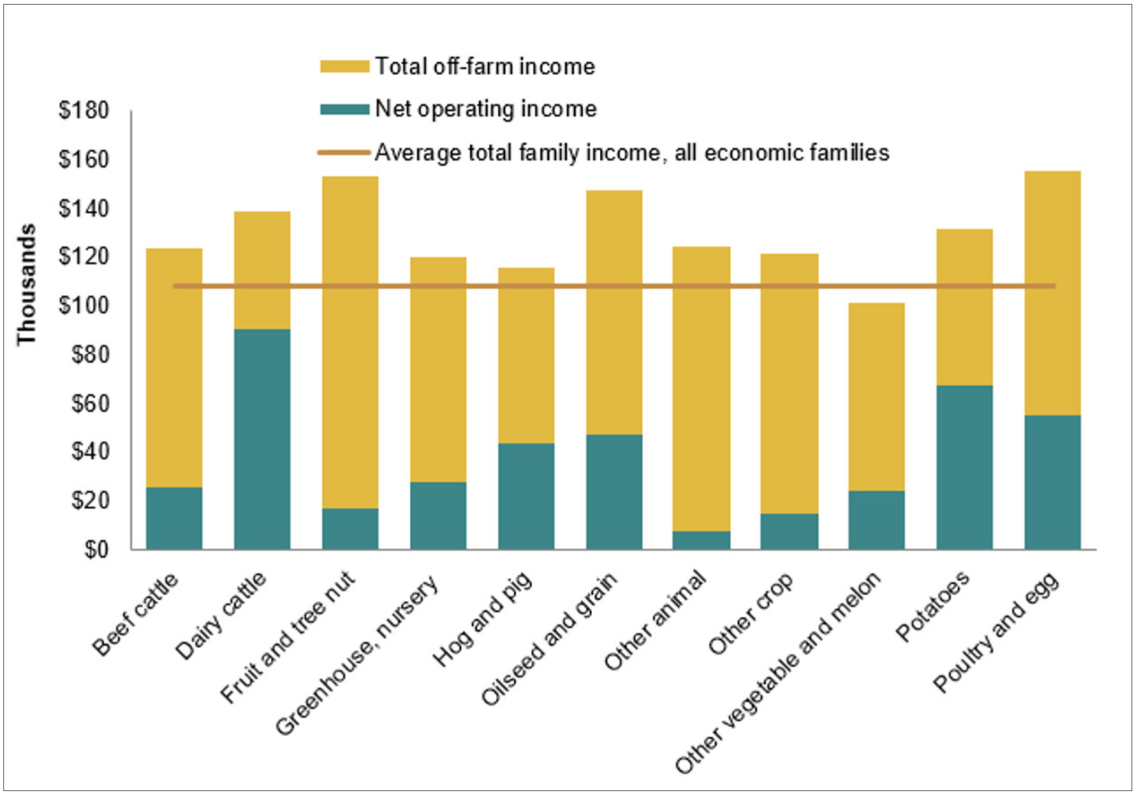


Figure 14-D. Annual total family income

Figures 14. Canada's agri-food sector

Source: Agriculture and Agri-Food Canada,2019.[120]

Acknowledged difficulties in the sector today include high reliance on migrant farm labour, and the poor profitability of many farms, where the high costs of inputs for conventional farming (seeds, chemicals, machinery) mean that debt burdens are high and even large operations can suffer from slim margins. More generally, Canada's agri-food industry has had trouble 'moving up the value chain'. Investment in R&D and machinery in the food processing industry has declined in recent years. For example, although interest in plant protein has led to growing exports of lentils it has not resulted in rising exports of plant-based food products. Other concerns with agri-food systems relate to health and Canadian diets, including the high salt and sugar content of processed foods, and the proportion of calories derived from meat.

Farming has a significant environmental footprint and is an important contributor to the two global problems of biodiversity loss and climate change. Biodiversity pressures come principally from the land appropriated for human purposes (about half of habitable land globally) and how the land is used (typically input-intensive monocropping).[157] In Canada about 7% of the total land area is currently in agricultural production, but this is often the most settled areas with the highest original biodiversity. Agriculture currently accounts for about 10% of Canadian GHG emissions. Lifecycle emissions from the wider agri-food system are larger as they include emissions from fertiliser production, the food processing and retail sectors, and transport (which are categorized under other headings in national GHG accounting). Other impacts include contributions to the global chemical pesticide burden, depletion or contamination of groundwater, and eutrophication of surface water due to fertiliser run off (causing toxic algal blooms and harming fisheries and recreational activities).

NATURE OF THE PROBLEM TODAY

The productivity of modern high yield cropping systems relies on mechanized operations with extensive application of nitrogen fertilisers and other chemical inputs, while large scale livestock production satisfies the demand for animal protein that forms a major component of Western contemporary diets. Nearly 90% of on-farm energy use came from fossil fuels in 2016. But this represented only a fifth of total agricultural emissions, with the bulk related to nitrogen fertiliser use, and manure and enteric emissions from livestock (especially beef and dairy herds).[228] Nearly a third of the country's methane emissions and three quarters of nitrous oxide emissions come from agriculture. Livestock operations account for about half of Canada's agricultural GHG emissions.

The expanded use of nitrogen fertilisers during the second half of the 20th century allowed substantial increases in agricultural yields worldwide. But today more than half of the reactive nitrogen in the environment comes from human sources including fertiliser application. Since 2005 inorganic nitrogen fertiliser use in Canada has increased by 72%.[228] To put this in context, Canada's current application rate of 87.6 kilograms per hectare of arable land remains well below levels in other developed countries (USA 138, Germany 197, UK 252).[122] Soil health on many Canadian farms has improved over recent decades with the widespread uptake of no-till agriculture (particularly in Western Canada) which allows greater water retention, avoids erosion, and increases soil organic matter.

The substantial GHG footprint of meat (mainly beef) production results from enteric emissions (33% of the agricultural total) and manure (11% of the total), but also from growing crops required for animal feed.[228] The comparatively low conversion efficiencies (the calorie or protein input required to produce a given output) of beef production are well known. One recent analysis suggested that for the US agricultural system protein conversions rates are about 3% for beef, 9% for pork, 14% for dairy and 21% for poultry.[146] In other words, pig and poultry farms are three and seven times more efficient than beef production in converting plant-based protein into animal protein. On the other hand, ruminants form part of natural grassland ecosystems; they convert fibres that are inedible to humans into high-quality protein; and mixed farming systems (using manure to fertilize crops and feeding crop residues to livestock) have been around for several thousand years.[138] Nevertheless, modern agriculture has vastly increased ruminant numbers.

The agri-food system will be one of the most complicated sectors to move to net zero.[177] Emissions are widely dispersed and difficult to measure. The sector is heterogeneous and the GHG footprint of production varies widely (even for the same product). Depending on conditions, soils can act as either net GHG sources or sinks. Complex corporate and political challenges have historically made intervention in the agricultural sector difficult. Conventional industrial agriculture tries to simplify and control ecological interactions (through monocropping, chemical inputs, etc.) to raise output.[150] But consequences for the wider environment (loss of biodiversity, pollution, GHG emissions) and production (loss of soil quality, requirements for increasing synthetic inputs, resistance to herbicides and pesticides) are serious.

Transforming the sector requires a rethink of established production paradigms and inevitably raises issues about what we produce (and eat) as well as how it is produced.[147,151,152] Most existing agricultural support programs focus on stabilizing prices, providing insurance against natural risks (hail, drought, disease, etc.), and encouraging exports. In some cases, they may encourage expansion of environmentally deleterious practices. Increasingly, however, there is recognition that sustainability (and documentation of a sustainable and low carbon supply chain) can be a competitive advantage both domestically and internationally.[162]

Debate and research continue over how agricultural systems can promote multiple values (local livelihoods, healthy food production, biodiversity enhancement, water quality, international exports, etc.). Profound change will be required to make agricultural systems sustainable. And while today we cannot fully characterize what those changes will be, we can identify key elements required to move forward.

NET ZERO PATHWAYS

Three elements must be in place to move agri-food systems towards net zero.

- **Displacing fossil fuel end-use on the farm** (and throughout the food industry). Conceptually the most straightforward change, which mirrors transformation of the wider economy, it faces additional challenges in rural conditions. Electrification, hydrogen (or a related net-zero energy carrier) and biofuels are the main options. Today fossil energy is used mainly for vehicles and machinery (trucks, tractors, harvesters, pumps, etc.) and heating (buildings, drying, processing, etc.). Light and medium duty vehicles can move to battery electric as societal electrification of the vehicle fleet gathers pace. Some light electric tractors have begun to enter the Canadian market. But significant improvements in battery energy density is required for heavy applications (large tractors, harvesters, excavators, etc.). Here hydrogen fuel cells hold promise, but their roll out requires low cost, low carbon hydrogen to be available in rural areas – and we are far from there today. Although biofuels are unpromising for vehicles nationwide, they have potential on the farm (for equipment and heating), particularly because local demand and feedstocks can be linked.
- **Reforming cultivation practices.** Multiple approaches are required to reduce inorganic nitrogen inputs, prevent loss to the environment of those that are used, and to improve soil carbon retention. These include no-till or low-till practices, the diversification of cropping systems, greater use of cover crops, improved crop rotations (often including pulses), more efficient application of inputs, and integrated agricultural management systems.[144] Managing the soil to improve fertility, raise organic content, prevent erosion and nitrogen release (from run-off or volatiles) will be at the center of this effort. Precision techniques for applying fertilisers, slow release and control-release fertilisers, and nitrogen inhibitors will be important. So too will be the adjustment of cropping systems to reduce reliance on fossil-based inputs. To some extent this involves a return to techniques (rotation, multi-cropping, green manures) that were largely abandoned in the heyday of high-input monocrop production. But older techniques will be combined with modern crop varieties, soil additives, big data, precision application, and so on.[155] Organic farming has established that in some circumstances cropping systems that avoid synthetic nitrogen can be productive, with the control of pests and weeds sometimes representing a greater challenge than soil fertility. And a significant research effort is required to discover and diffuse the best techniques for different crops in variable soil and climate conditions.
- **Addressing animal agriculture.** Two basic approaches are available:
  (a) Adjusting livestock production practices and technologies to reduce associated emissions. The GHG performance of the Canadian beef industry has improved significantly over past decades, with emissions per kilogram of beef now below half the world average. Multiple techniques are available to secure further progress, including improved animal genetics, higher quality feed, food additives to reduce enteric emissions, more sophisticated

manure management systems, changed grazing practices, and better soil management. In some circumstances it may be possible to produce beef and dairy with very low (or even net negative) emissions. How far this can be replicated for Canadian producers more generally remains an open question.

b) Shifting production and consumption towards alternative protein sources. Over the past 40 years per capita beef consumption in Canada has declined by 37%, while the place of chicken in the diet has grown by more than 80%. Continued movement to meats with higher protein conversion efficiencies (especially poultry or some farmed fish) could contribute to reduced emissions. A more dramatic change will involve:

- **Increased emphasis on plant-based proteins.** Over the past decade, meat substitutes (eg. vegetable-based burgers) and alternative 'milks' (soya, almond, wheat) have achieved commercial success. The trend has been driven by consumer concerns over health (and to some extent animal welfare and climate change) but also by advances in processing that have allowed improved flavors and textures in meat substitutes.
- **Proteins created through fermentation or tissue culture.** Biotechnology advances have dramatically reduced the cost of creating animal proteins through enhanced fermentation.[137, 145] The milk protein casein has already been incorporated into ice cream in the United States, and research on cellular meats is proceeding rapidly. Producing proteins without growing a whole animal could offer dramatic GHG reductions linked to manure and ruminant digestion, and fertilizers (feed production), freeing up agricultural land for other purposes. Still, the potential health and environmental impacts of widespread adoption of these technologies have yet to be fully explored and the level of consumer acceptance is uncertain.

Transforming livestock practices concerns producers directly – with the industry changing the way it supplies traditional foods. This can be driven by regulation and incentives, by consumer concern about the climate footprint of animal agriculture, and the competitive advantage that accrues to producers who can claim low or net zero beef or dairy. The shift towards alternative plant-based foods involves consumers more directly in embracing changing diets. There is increasing scientific evidence that diets high in fresh vegetables, pulses, nuts, and fish, with only moderate quantity of animal protein, are conducive to health.[148,158] Although the proportion of the population committed to vegan principles remains small, there is a broad tendency to reduce consumption of red meat and dairy-based beverages. Fermentation-based proteins and cultured meats raise issues about the public acceptance of engineered foods. But demand is not exogenous as the agri-food industry actively shapes consumer tastes and habits. Moreover, the initial impetus for incorporating fermentation proteins in manufactured food products will be cost-led (ie it will be cheaper to get protein from a vat that from a cow).

Two additional issues must be considered:

- **First, loss and waste occur across the food system: from the farm, through processing, distribution, and retail, to restaurants and households.** [139, 140] The scale is staggering, with some analysts suggesting that more than half of all food is currently lost. This significantly amplifies the environmental footprint of the agri-food system and suggests substantial GHG reductions could be secured if food loss and waste were minimized. Until recently the tendency has been to locate much of the problem at the household level (overbuying, poor meal planning, spoilage, disposal of still viable produce, etc.). More recent work points to waste in processing, production, and manufacturing.[141] Raising consumer awareness may be important, but individual behavior change is unlikely to get far. Instead, initiatives are required all along the supply chain, so the full environmental costs of waste are better integrated into the design, production and distribution and marketing of food.
- **Second, agricultural practices, and changing land use patterns related to agriculture, can lock up carbon, potentially generating negative GHG emissions.** This could off-set residual emissions from elsewhere in the agricultural sector or other parts of the economy. Enhanced carbon storage in soils, and the restoration of grasslands, wetlands, or forests released from agricultural production (because of increasing agricultural productivity, large-scale adoption of plant-based or alternative proteins, etc.), could make this possible. Yet the uncertainties are substantial, with lively debates continuing among experts over how far the carbon content of soils can be raised, the potential of treatments such as bio-char, and the impacts of a warming climate on biological sequestration.[142, 143]

Net zero pathways in different branches of the agri-food system will involve combinations of these elements. The problem is made more complex by the export-intensity of Canadian agriculture since domestic production and domestic consumption are only loosely coupled especially in the beef and grain sectors. Even if Canadians embrace diets richer in plant-based proteins, this will not necessarily lead to lower GHG emissions from the agricultural sector if raising demand for meat in developing countries leads to increased Canadian production, or pulse production is expanded without emission abatement practices. On the other hand, a significant international turn towards fermentation or cultured meats could ultimately erode export markets for Canadian beef.

There is no simple 'one size fits all' solution for moving agri-food systems onto a net zero trajectories.[153, 154] A variety of alternative agricultural paradigms could offer parts of the solution. These include 'organic agriculture' which avoids synthetic inputs (including nitrogen fertilisers), 'precision agriculture' which uses site and plant specific information for tailored input application (reducing fertilizer run off),[236] 'vertical farming' that stacks production indoors (potentially reducing chemical use and facilitating electrification of machinery),[237,238,239] 'regenerative agriculture' that focuses on soil health,[234,235] and 'low input agriculture' that minimizes fossil-derived inputs in part to improve the farm balance sheet.[240] But none of these offer a magic bullet. There are longstanding disputes over the relative merits of conventional and alternative practices (e.g. organic farming), with some research suggesting high yield approaches are better for biodiversity or climate because of the additional land required by alternatives.[153] But if it seems hard to imagine converting all agriculture to organics (which presently account for 1.8% of farmland in Canada), addressing climate change nevertheless requires a decisive move away from business as usual. Considerable practical experimentation and research, including participatory plant-breeding and on-farm research will be required to develop approaches suited to different conditions, regions, and sub-sectors.[156]

SHORT- AND LONG-TERM PRIORITIES.

Short-term actions can focus on accelerating change where options are already available, intensifying research, trials and scale up of more sustainable cropping and livestock practices, reforming farm support programs to favor climate adaptation and mitigation (and more generally the promotion of agroecological stewardship), and enhancing training and practical exchange of experience.[159,160,161] This can be integrated with efforts to address other challenges including farm debt, high land costs, the difficulty of attracting young farmers, and corporate concentration.[159]

Reform of agricultural support mechanisms is already under active discussion, and emphasis on mitigation of GHGs and resilience in face of climate risks could be built into program design. Measures can focus on enhancing soil health, encouraging cover crops, increasing biodiverse buffers, planting trees, rehabilitating wetlands, and so on. Canada has a long tradition of successful agricultural research involving collaboration among universities, federal and provincial governments, and farm groups. Yet the public organizations and farm extension services which disseminated best practices and provided farmers individualized advice have been defunded and replaced in recent decades by privately funded services connected to input and equipment manufacturers. The climate challenge is sufficiently serious to consider reestablishing government funded research, education, and outreach institutions to promote sustainable agricultural practices. This can include specialized programming to support young farmers, Indigenous farmers, women and newly arrived Canadian farmers.

Agri-food supply chains (that link production through processing to end users) have a critical role in transforming the sector. Although direct emissions come mainly from the farm, they result from the wider system, and the coordination of actors through supply chains can accelerate innovation, channel resources, and manage risk to allow farmers to adopt more climate-friendly practices. Food processors and distributors can play a major role in building innovative and collaborative supply chains that mobilize knowledge, capital, and organizational capacity to work with primary producers to accelerate change.

Recently there have been promising initiatives to promote Canada as a sustainable agri-food producer (and to document the integrity and life-cycle footprint of supply chains) and this could grow markets for Canadian products while accelerating a greening of production. Encouraging the food industry to invest more in plant-based processed food products, and to explore the potential of fermentation-based or cellar meat (including more thorough assessments of their health and environmental implications, and public receptivity) should also start now. On the consumer side, public education around healthy diets, food safety and the environmental footprint of foods are important. Measures to encourage closer connections between suppliers and consumers (for example, through local markets) can raise consumer consciousness and support farm incomes.

Reduction in dependence on synthetic nitrogen fertilisers is a priority. Multiple approaches are possible including improved fertilisers (coatings, inhibitors), new crop varieties, precision fertilizer application, and alternative cropping systems that build soil fertility. Consideration should be given to regulating fertilizer manufacturers to increase the market share of more benign products (analogous to mandates requiring automakers to produce zero emission vehicles).[121] Animal agriculture needs to be addressed more vigorously by encouraging a portfolio of techniques to reduce ruminant emissions from beef and dairy herds as well as more successful manure management.

Promoting the uptake of battery electric or hydrogen fuel cell machinery and vehicles, on farm renewable electricity generation, on farm use of locally produced biofuels, and energy efficiency (insulation of houses, barns, storage, and drying facilities), can start to lessen dependence on fossil fuels. Agricultural producers today often benefit from fuel tax exemptions, and mechanisms must be found to incentivize the shift to low carbon fuels and increase energy efficiency.

Over the longer term, it will be important to support research and trials of alternative agricultural paradigms, integrate GHG management into all aspects of the agri-food sector, and establish more clearly the parameters for achieving negative emission through soil management practices and land use change.

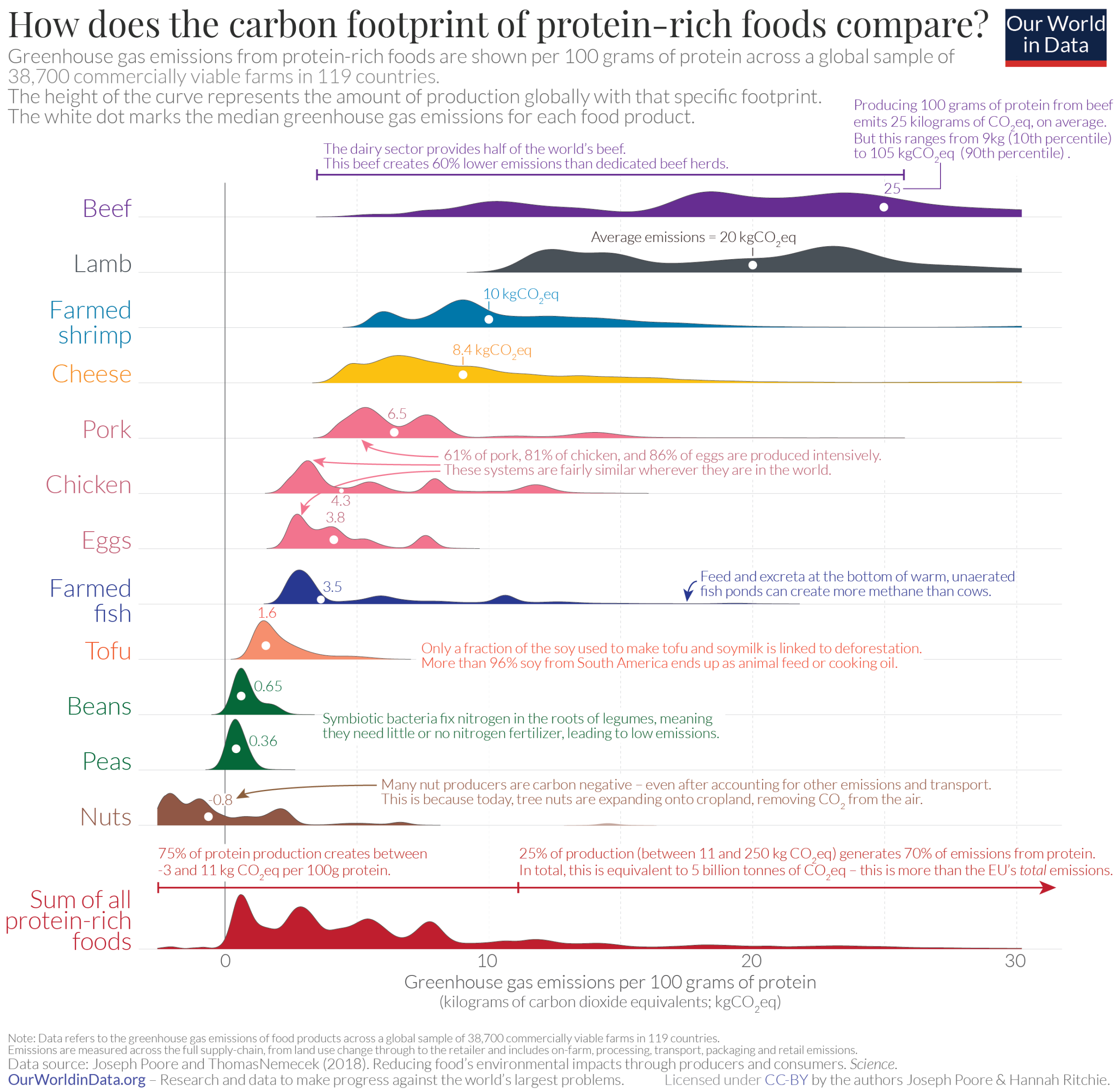


Figure 15. Comparing carbon footprints of protein-rich foods

Source: OUR WORLD IN DATA (https://ourworldindata.org/environmental-impacts-of-food)

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Agriculture and agri-food**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
On farm energy use									
Battery electric farm equipment	Entering market but further battery development required for heavy loads	Will improve over time	No particular concerns	Yes, for lighter duty. But battery weight currently prohibitive for heavy duty vehicles	Yes, assuming net zero electricity supply and manufacture of equipment	Potentially to equipment manufacturers.	Clean operation. Reduced noise. Less maintenance. Challenge of battery recycling	Yes, for electric equipment manufacture	Yes . Potentially part of zero emission world
Biofuels for heavy farm equipment	Mature. Established technology	More expensive that fossil fuels today	No particular concerns	Yes.	Yes, depending on full lifecycle of the biofuel.	Yes, familiar to farmers. Appeals to producers.	Local production/ consumption Contributes to air pollution	Particularly for local producers	Medium to high. Potentially part of a low emission world
Hydrogen fuel cells for heavy farm equipment	Fuel cell technology is reasonably mature. But applications for heavy equipment require further work.	Low at present because hydrogen infrastructure not built out and fuel cell adaptation for heavy equipment not complete	Some concerns over safety of hydrogen fueling	Yes.	Yes. If hydrogen is made from decarbonized electricity such as renewables or from fossil sources with CCS and offsets. Longer term viability of fossil-based hydrogen depends on CCS and offset availability	Potentially compelling if hydrogen supply issues addressed	Improved driving (torque), lower maintenance, no air pollution, noise reductions	Good. Opportunities for fuel cell manufacture, equipment manufacture, and hydrogen production	High. Potentially part of net zero emission world
Renewable power generation (wind, solar, biomass)	Wind and solar, are mature. In practice biogas production (and manure digesters) can pose technical challenges.	Depends on the application. As cost and efficiency of solar continues to improve economics look more favorable.	Fine at farm scale. Some opposition to utility scale development on farmland	Yes, as a supplement to grid power. Stand alone systems (fulfilling all farm needs) more rarely.	Yes, compatible with a net zero future	Yes, can reduce farm energy costs.	Biomass systems can aid with manure and farm waste management. Can reduce pressure on grid.	Yes, but mainly local	Medium to high
Crop agriculture									
More efficient fertiliser use (Improving fertilizer source, rate, timing and placement)	Multiple technologies still evolving: EG: coatings for timed release, precision application (using sensors, data analytics, etc.)	Yes, many already coming to market	No particular issues from the public	Precision inputs can reduce waste and enhance profit and yield. Allows immediate reductions in N fertiliser use	Can dramatically reduce nitrogen emissions (if combined with CCS on fertiliser manufacture). But some escape to environment remains. So not net-zero on its own	Can appeal to farmers and fertiliser producers. But many farmers are risk adverse to changing established practices.	Reduction of ground water leaching, eutrophication, potentially improved soil health, lower input costs.	For companies producing improved fertilisers, production, precision application and analytics systems	Medium to high. Can be part of zero emission systems if offsets found elsewhere.
Improved crop regimes	Multiple approaches including complex rotations, cover crops, green manures. Many are well established, but research required to perfect for different regions/crops	Yes, for established practices. But defining individualized solutions can require practical experiments and be costly to the farmer	Yes, no particular issues	Yes. Over the longer term, yields can be stabilized or increase.	Yes, with appropriate approach for given crops, soils, and climate.	To some producers.	Improved soil health, water retention, reduced erosion, increased biodiversity	Can improve viability of farm operations.	High priority for research, trials deployment Key element of net zero agriculture

Fails to meet criteria | Not promising | Meets in some respects | Potentially meets criteria | Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Agriculture and agri-food**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Animal agriculture									
Manure management	Multiple techniques at different levels of development	Depends on approach.	No particular problems.	Yes.	Can contribute to significant (and immediate) reduction in emissions. But some escape to environment remains. So cannot meet net-zero on its own	To some producers, equipment suppliers	Improved nutrient retention, reduction in environmental burden	Unclear	High. Will be necessary for net zero animal agriculture
Food additives, food mixes, vaccines	At different stages of development	Depends on approach	No particular problems.	Yes	Can contribute to reduction in emissions. How far it can go to deal with enteric emissions remains to be seen	To producers of additives, novel food mixes, vaccines. For farmers potential non-disruptive way to reduce emissions	Shift to grain or oilseed crops in beef and dairy livestock diets could reduce economic viability of native prairie habitat (leading to biodiversity loss)	For producers of additives, food mixes, vaccines	Medium to high
Enhanced animal genomics	Continuously being developed	Yes	No particular problems.	Yes	Can contribute to reduction in emissions. But how far remains to be seen.	To suppliers and farmers (cost savings). For farmers potential non-disruptive way to reduce emissions	Higher production efficiencies. Potential for reduced herd size and environmental footprint	To industry. Canada has a significant breeding industry.	Medium. With other approaches
Dietary and production shift to plant-based proteins	Technologies already mature and new products being developed continuously	Yes. Can offer substantial cost savings for food producers (as compared to animal protein-based foods)	No particular problems. Increasingly positive social resonance	Yes, products can provide good nutrition. But concern over high salt, fat, sugar and additives in many products	Yes. Depending on net-zero crop agriculture practices.	Export market opportunity for Canadian agricultural producers.	Health benefits to consumers. Reduced environmental load from animal agriculture. Released land from animal agriculture. Some concerns of biodiversity loss from decline of extensive livestock systems in prairies.	In developing plant-based food products	High. But requires long term cultural shifts
Dietary and production shift to synthetic proteins	Fermentation: fundamental techniques well established, but still emerging for food (as opposed to pharmaceutical products). Cellular meat: still at research phase	Cost for fermentation falling rapidly, soon to be competitive for milk proteins. Cellular meat still at research stage.	Questions about consumer acceptance of lab grown meat.	Fermentation: yes. Proteins can substitute into the processed food industry with minimal disruption. Cellular meat: less clear about functional and nutritional characteristics.	Yes, in principle depending on growing of plant material used as feedstocks, chemicals required in the process, decarbonized energy inputs, and waste disposal	Can appeal to food processors (lower cost inputs than proteins from livestock) and companies involved in biotechnology.	Potential reductions in agricultural land (currently used for animal agriculture, feed production) and chemical inputs. Potential health benefits and risk: benefits reduction of animal born disease, antibiotic use and tailoring of protein production to human needs. Risks, nutrient loss, unforeseen issues.	A new industry to be built from the ground up. Balanced by potential loss of livelihoods in the dairy, beef and other livestock sectors.	Medium (For now until further knowledge of potential, impacts, etc.)

Fails to meet criteria	Not promising	Meets in some respects	Potentially meets criteria	Meets criteria

* For explanation of criteria see Box B, page 22

ASSESSMENT TABLE: **Agriculture and agri-food**

	Credible			Capable		Compelling			Priority approach
	Maturity	Economic viability	Social acceptability	Fit for purpose	Net-zero pathway potential	To critical stakeholders	Related costs and benefits	Economic development opportunities	
Agricultural paradigms									
No till agriculture (minimizes soil disturbance)	Already widely practiced especially in western Canada	Yes, saves money on heavy machinery and fuels.	No issues	Yes. But challenging for some crops (eg potatoes, beets) and in some soils. May not be practical indefinitely in some contexts	Yes. But on its own does not reach net zero. Needs to be combined with other cropping practices.	Yes, already adopted by thousands of farmers. Manufacturers are already making light equipment to avoid soil compaction	Reduces erosion, increases moisture retention, raises organic matter. Can promote carbon sequestration	Already widely adopted so these are already largely achieved	Medium. Mainstream but more could be done in Eastern Canada
Organic agriculture (avoidance of chemical inputs)	Already widely adopted for many farm outputs (grains, vegetables, dairy, beef, etc.). Continuously advancing techniques.	Yes, but to some extent depends on the premium organic products command. There are high costs for certification	Positive public image. Sector continues to expand	Yes. But challenging with some crops. Yield penalty for many crops.	Depends on the practices. Animal agriculture can still emit substantial GHGs unless appropriate measures are adopted.	Yes, to some farmers and many consumers. Sector still expanding	Reduces chemical burdens on environment (pesticides, fungicides, etc.) and residues in food. Debate ongoing over whether it improves nutritional quality of foods.	Significant. Only 1.5% of agricultural land is farmed organically today. This could be substantially raised over time. Production does not satisfy consumer demand in Canada. Potential export markets	Medium
Precision agriculture (applies inputs tailored to conditions)	Already being deployed: monitoring equipment, machinery for weeding, fertiliser application, etc.	Substantial capital investment. Input savings may not be sufficient to cover costs unless the latter decline.	No particular problems.	Yes, water nutrients, treatments are delivered in appropriate amounts.	Could contribute to much lower nitrogen emissions. But how low this can go remains to be seen.	Yes, for manufacturers of precision equipment, data managers, and potentially farmers due to reduced input costs.	A variety of environmental benefits.	Yes for major suppliers of machinery and inputs	Medium to high
Vertical agriculture (Stacked cropping in greenhouses or fully controlled indoor environments often using hydroponics, aeroponics, etc.)	Based on decades of greenhouse agriculture, but stacked techniques, mechanization and robotization, still developing.	Yes, for high value crops, close to markets (leafy vegetables, tomatoes, and increasingly soft fruit) and plant propagation. Potential for remote communities	No particular problems.	Yes, but not applicable or economic for all crops – for example potatoes, grains, tree fruits, etc.	Yes, if lighting, heating, ventilation, etc. powered by net zero technologies, and wastes managed appropriately.	Yes, particularly for producers near large urban markets, or in remote communities.	Reduction in need for water, chemical inputs, pollution from waste and land required. Fresher produce can be delivered to nearby markets. Production can be linked closely to consumer demand.	Yes, for equipment manufacturers. Enterprises in remote communities.	Medium. Important, but scale at which it can be applied is still uncertain
Low input agriculture (hybrid that minimizes external inputs)	Still emerging as a hybrid. Many elements already well developed, others emerging	Depends on yield/input trade offs and particular techniques	No particular problem	Potentially. But remains to be seen if yields can be kept high enough	Yes. But low input does not necessarily entail net zero emissions. It depends on the actual practices and input/output relationships	Potentially appealing to farmers as alternative to conventional model	Reduction in pollution burdens. Unclear whether more land required	Unclear	Medium to high

6. Conclusion

This report has explored pathways to net zero in Canada, focusing on the evaluation of pathway elements in key systems and sectors. It has applied a transition and energy systems perspective that emphasizes the need for change across multiple systems of societal provisioning to meet climate objectives, and the importance of keeping in mind a vison of the energy system that will be required to meet the needs of a future net zero society. **A critical insight of this perspective is that policy and investment should be oriented towards reconfiguring these major systems — to deliver net zero and other societal improvements — rather than being preoccupied with lowest cost incremental emissions reductions to achieve short term targets.**

The report has not primarily been concerned with detailed policy design – but rather with identifying the strategic areas where policy and investment can be brought to bear to accelerate change. In focusing on these systems and sectors we recognize that:

- **there are complex connections among systems and sectors** that will influence the journey to net zero. Most obviously, the electricity system will be expected to bear increased loads as transport and heating shift away from end use fossil fuels. And the fossil fuel production sector will be impacted by a corresponding fall in the domestic demand for oil and gas. But there will be other interactions as new energy carriers replace fossil fuels and sectors expand, contract, and readjust.
- **the international context will have a major impact** through the evolution of international agreements on climate change, global technology development (energy and low carbon innovation, but also autonomous vehicles, artificial intelligence, biotechnology, and so on), and changing patterns of trade as foreign economies are increasingly decarbonized (reduced demand for Canadian fossil fuels, potentially increased demand for minerals or forest products); and so on.
- **provinces and regions will combine elements in different ways** to define distinctive pathways that reflect their resource endowments, economic strengths, political choices and cultural traditions.

In the discussion of specific systems or sectors we have tried to integrate these cross sector, international, and regional dimensions. Notwithstanding these and other complexities, the focus on major systems and subsystems or sectors allows the identification of strategically significant pathway elements that must be advanced if overall movement towards net zero is to be secured.

In one sense moving to net zero is straightforward. Just decarbonize electricity generation and expand supply to eliminate fossil fuel end use; develop and deploy net zero fuels to replace fossil fuels in situations where electrification is difficult or expensive; enhance energy efficiency to reduce the need for net zero energy supply; address non-energy emissions (waste, industrial processes and products, agriculture); and explore carbon removal to offset residual emissions. But this must be done across different systems/sectors that fulfil essential needs, each with their own dynamics and constraints, and in a context where changes in demand, patterns of daily life and individual and collective priorities can facilitate or hamper decarbonization. Moreover, multiple technical, social, business model, regulatory, and attitudinal elements must be integrated over time to achieve substantial system realignment.

Confronted with this challenge, instead of muddling along – doing a little bit of everything and waiting to see what turns up – it is essential to focus on the systems and pathway elements that can make the largest contribution to achieving net zero and to adopt measures tailored to the particular context and transition phase. In sectors (or subsectors) where solutions are available, that means accelerating large scale deployment and pushing towards system reconfiguration. Rapid change here can facilitate movement elsewhere by establishing the profitability of low-carbon investment, showing change is possible and inevitable, and weakening demand for end use fossil fuels. In sectors where solutions are not yet mature this means accelerating research, pilots, and large-scale experiments to prepare for future mass deployment (see Box A on page 12 for a discussion of policy measures tailored to each transition phase). We have spelled out what that means for the sectors discussed in this report in the pathway assessments in Section 5.

For electricity this means advancing towards full decarbonization of the sector (coal phase out, replacing unmitigated gas with renewables and other zero-emission options); improving system capacity to integrate and deliver affordable, resilient net zero electricity (regional interties, storage, grid improvements, demand management, etc.); and incrementally expanding generation to handle increased loads from the electrification of transport and heating. Priorities differ by province. Over the medium-term electricity/hydrogen integration can enable a fully net-zero energy supply.

For transport it means encouraging a rapid transition to electric (light and medium duty) vehicles and the build out of the zero-emission vehicle supply chain in Canada. The bulk of this shift could be achieved in 10-15 years or in 15-25 years, with huge economic consequences for Canada depending on whether the country becomes an international leader or a laggard. The encouragement of active mobility and the continued extension and upgrade of electrified mass transit systems are also important. Heavy freight requires the development, demonstration, and subsequent rollout of practical solutions (such as hydrogen fuel cell trucks and trains).

For buildings it implies measures to improve the performance of all new builds (strengthened codes), pilots of mass retrofits, and roll out of systematic programs to upgrade existing structures so the building stock as a whole can meet net zero standards. For heating, electric options are already practical, and research, development, and pilots for hydrogen heating (and in some case renewable gas) should be accelerated.

For heavy industry solutions vary by sub-sector, depending on the nature of their product, energy demand and process emissions. Defining trajectories for specific industries that dramatically curtail emissions (through fuel shifts, process improvements, output changes, etc.) is a first step. But then the technological innovations and business model adjustments must be carried forward in practice as solutions reach maturity.

For agriculture immediate efforts can be made to reduce emissions from nitrogen fertilizers and animal agriculture. But transition is in a relatively early phase, and there is a need for research, demonstration, practical experiments, and collaborative learning to map out broader transformative pathways.

Among the cross-cutting issues which have emerged in the discussion three deserve mention here. **The importance of energy efficiency** – which reduces the scale of the low carbon energy supply which must be delivered to end use sectors (buildings, appliances, equipment, etc.), the speed with which they must be deployed and the costs of transitions. **Developing hydrogen as an energy carrier** (rather than just as an industrial feed stock as it mainly functions today) which can find application in multiple sectors including storage to facilitate deployment of intermittent renewables. And **negative emissions approaches** which remain highly uncertain (technical viability, permanence, practical scale, costs), and here the challenge is to conduct research, development, experiments and assessment to evaluate their real potential and the circumstances under which they could or should be deployed.

In policy terms, specific measures are required to accelerate change in each sector and subsector, with multiple instruments integrated into packages to achieve goals appropriate to the transition phase. Often these will include policies to develop and encourage the uptake of specific technologies, as well as to mandate the phase out of fossil fuel dependent technologies and practices.

But there is also a need for economy-wide policies to encourage transition: carbon pricing that signals the undesirable character of GHG emissions; low carbon public procurement to strengthen niches for emerging options; low carbon finance mechanisms to mobilize capital for transition; and support for clean technology research, development and deployment and social innovation to open pathways for future rapid change.

Summary Tables

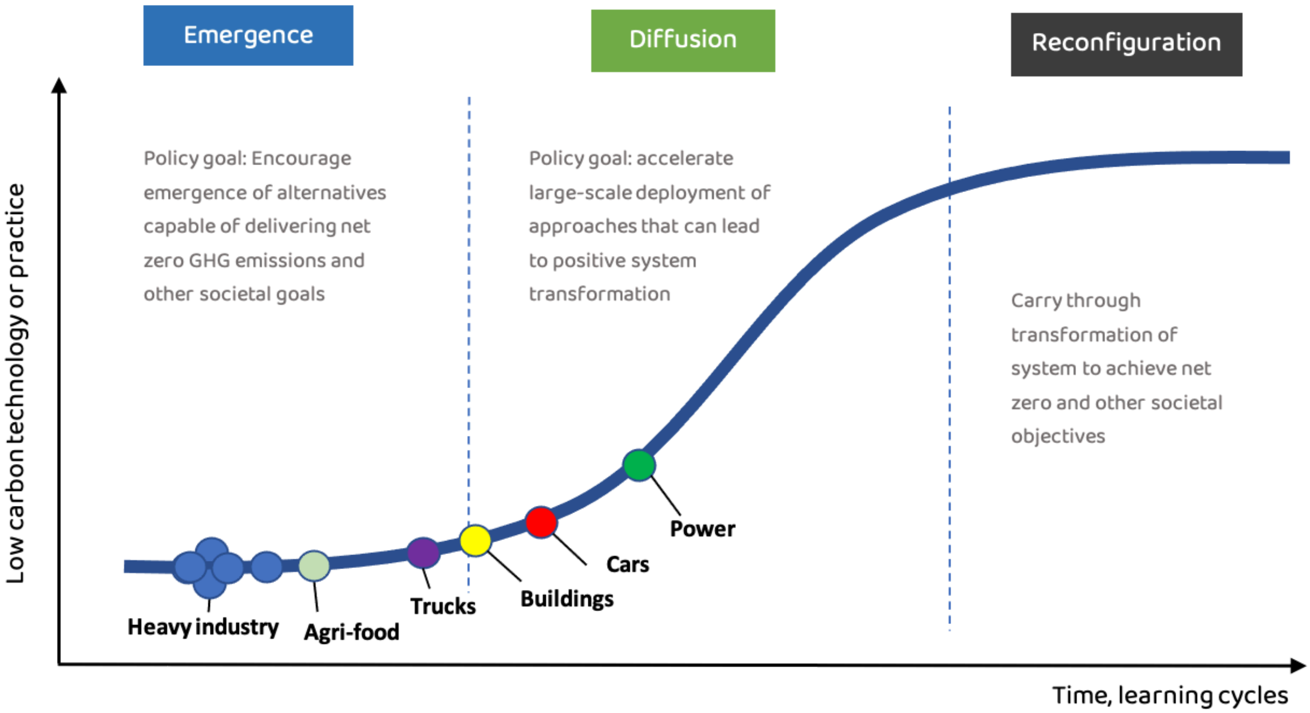


Figure 16. Progress of low carbon transition.

Adapted from Victor, Geels and Sharpe, 2019 [81]

Priorities for key sectors

POWER

9% OF CANADIAN EMISSIONS

DIFFUSION

Multiple low carbon generation options. Will assume transport and other loads as decarbonization progresses.

ACTIONS: Priorities differ by province: Phase out coal; integrate renewables and other net zero sources; Improve system capacity to deliver reliable, affordable net zero electricity (grid interties, storage, demand management)

CARS

13% OF CANADIAN EMISSIONS

EARLY DIFFUSION

Innovation stabilized around electric vehicles for personal cars and light trucks. Critical to break fossil energy dependence in transport.

ACTIONS: Accelerate EV adoption and build value chain for manufacture of zero emission vehicles. Invest in charging infrastructure. Zero emission vehicle standard. Fix phaseout goal for gasoline cars.

BUILDINGS

13% OF CANADIAN EMISSIONS

EARLY DIFFUSION

Advanced building approaches and electric heating mature. 'Green gas' options immature. Systematic retrofit of existing structures is critical.

ACTIONS: More stringent codes for new builds; regulatory standards to drive improvement in existing buildings; public procurement to support sector transformation; pilot mass retrofit approaches; develop mechanisms to mobilize private capital for retrofits.

HEAVY TRUCKS

9% OF CANADIAN EMISSIONS

EMERGENCE

Heavy vehicle options require further development to enter market at scale.

ACTIONS: Vehicle development R&D, trials at scale, infrastructure investment, low carbon hydrogen production, zero emission vehicle mandate, public procurement, support for fleet conversions.

Priorities for key sectors (CONT'D)

OIL & GAS

26% OF CANADIAN EMISSIONS

EMERGENCE

Approaches to net zero fossil fuel production and net zero energy production from fossil resources are immature. Traditional production wind down necessary for net zero.

ACTIONS: Dramatically improve energy efficiency and emissions profile of existing oil and gas extraction. R&D and infrastructure for zero emission fuels production (hydrogen or electricity), geothermal energy, and materials. Scale back all investment in the sector not geared to an ultra-low emission future.

CEMENT

1.5% OF CANADIAN EMISSIONS

EMERGENCE

No single pathway has emerged. Fossil energy can be replaced by electricity, hydrogen, or biofuels. Process emissions can be addressed by CCS or changing cement chemistries. Novel building materials could reduce cement demand.

ACTIONS: R&D and demonstration projects to address energy and process emissions. Changes to procurement and building codes to establish market for low carbon cement.

MINING

1% OF CANADIAN EMISSIONS

EMERGENCE

Electric and hydrogen fuel cell equipment; on-site renewable electricity generation; advances in processing technologies and efficiency; recycle metals and reduce use.

ACTIONS: Support for advanced ore movement and processing technologies. Electrification of operations. Develop low emission mining to service expanded material needs of net zero societies

AGRI-FOOD

10% OF CANADIAN EMISSIONS

EMERGENCE

Approaches to address emissions from animal agriculture and nitrogen fertilizer use are in development. Sustainable farming and food system models remain immature in this diverse sector.

ACTIONS: Research, trials and promotion of alternative crop regimes and technologies to reduce nitrogen fertilizer use, improve manure management and reduce enteric emissions. Encourage production and consumption of alternative proteins. Decarbonize on farm energy use.

Notes

A) UNDERSTANDING NET ZERO

Although the basic idea of net zero emissions is relatively straightforward – no net release of climate forcing gasses, with residual emissions cancelled by removals – operationalization is complex.[123,133] Issues include:

- whether net zero refers to carbon dioxide emissions or all GHGs
- the accounting unit to which the commitment is applied (the globe, a country, province, city, sector, supply chain, and so on)
- whether all emissions reductions and removals are to be within the unit (some countries, for example, intend to secure part of their reductions or removals abroad)
- the target date for attaining net zero (for example, 2050), and the accounting period (for example, a year)
- the split between emissions reductions on the one hand, and residual emissions and removals on the other (for example, 60% emissions reductions from the base year, 40% residual emissions and 40% removals; or 95% emissions reduction, 5% residual emissions and 5% removals; and so on.
- the allocation of emissions reductions and residual emissions across regional or sectoral sub-units.

For this report net zero is understood to include all GHGs. The focus is on Canada and key sectors/systems of societal provisioning. We assume net zero is to be met within the country (not by financing emissions reductions or removals elsewhere). In line with the current government's commitment we adopt a 2050 timeframe. Since there are significant uncertainties about GHG removal approaches (including feasibility, cost, permanence, side effects, and so on) transformations that reduce emissions are the priority.[123] We assume all sectors have net-zero objectives and are actively engaged in driving emissions down. While pathways to virtually eliminate emissions from some sectors are already clear (e.g. electricity production), in others it remains uncertain how far emissions can be curtailed (e.g. agriculture). Over time, as systems adopt configurations with ever lower GHG emissions, the scale of withdraws required to achieve net zero will become clearer, and knowledge about removal technologies will have advanced. Since the intent of this report is the assessment of transition pathway elements (and not detailed policy design or characterization of the emissions abatement trajectory), these assumptions suffice to ground the analysis.

B) ENERGY USE AND EMISSIONS FIGURES

Throughout this report the figures (absolute numbers and percentages) related to energy use and emissions should be understood as reasonable approximations of reality. There are many challenges with measuring and accounting for energy flows and emissions, with differences among various data sets and accounting frameworks, and challenges allocating emissions to subsectors, processes, and activities. But the level of precision supplied here is adequate to purposes we have of evaluating the potential significance of pathway elements across multiple sectors.

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