Achieving Net Zero 2050 in Canada:

The Critical Roles of Forest Adaptation, Biomass, and Carbon Capture and Storage

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Background. With the recent submission of a revised Nationally Determined Contribution under the Paris Agreement, the government of Canada has established a year 2030 target to cut Greenhouse Gas (GHG) emissions by 40-45% relative to emissions on record for 2005. In addition, Canada is part of a growing list of countries with a stated intention to arrive at Net Zero (NZ) emissions by 2050.

Recently, the Trottier Energy Institute in collaboration with the e3c Hub and ESMIA Consultants released Canadian Energy Outlook 2021 (CEO 2021) (1). This report was based on a detailed energy-economy-environment integrated system of modelling of scenarios under optimum energy and climate strategies. Scenarios arriving at net zero emissions in 2045, 2050 and 2060 were assessed.

Figure 1 is taken from the CEO 2021 report and shows projected future emissions by economic sector under the various scenarios. With the NZ50 scenario, emissions rapidly decline across economic sectors with the exception of agriculture. However, by mid-century, substantial residual emissions, in the order of 130 Mt CO_2 equivalents per year (CO_2e/y) (18% of current levels), continue to be released from the combination of agricultural practices and other difficult to abate sources. To arrive at NZ50, these emissions must be offset by nature-based solutions and industrial processes that withdraw an equivalent amount of CO_2 from the atmosphere.

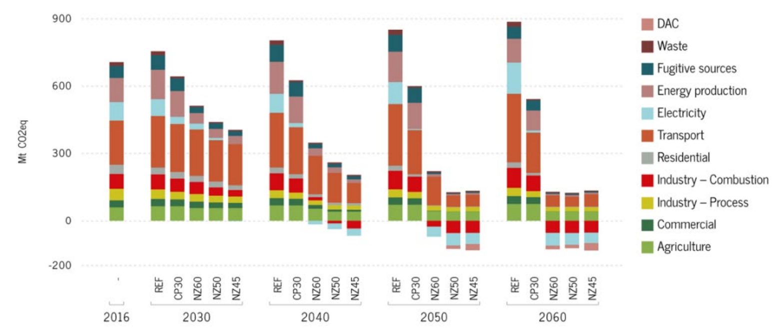


Figure 1. Total GHG emissions in Canada by sector and scenario. REF – Reference scenario based on policies currently in place without further constraints on emissions. **CP30** – Carbon pricing (reaching \$170/t CO_2e by 2030) is imposed on the reference scenario without further constraints. **NZ60** – Net-zero emissions target for 2060 with interim targets of a 30% cut by 2030 and an 80% cut by 2050. **NZ50** – Net-zero target for 2050 with a 40% cut by 2030. **NZ45** – Net-zero by 2045 with a 45% cut by 2030. Interim emissions targets are relative to emissions on record for 2005. Reproduced with permission from the Horizon 2060 Canadian Energy Outlook 2021 (1).

Mid-century targets of Net Zero emissions are often construed as aspirational and distant to the immediate concerns of government, industry, and citizens. However, long-term objectives to limit the damage potential of climate change are dependent upon immediate action. Achieving Canada's short-term goal of a 40-45% cut in emissions by 2030 is integral, and essential, to meeting mid-century aspirations of transitioning to a Net Zero economy.

The critical role of atmospheric CO_2 withdrawal in achieving ambitious emissions reduction targets is often not given due consideration. Policy development and funding tends to focus on cutting emissions in the traditional energy, electricity generation, transportation, industry and buildings sectors. These objectives are important but must be integrated with atmospheric withdrawal if Canada is to achieve near-term emissions reduction targets and to establish the pathways of transition to a Net Zero future.

A detailed assessment of Canada's forest management, agricultural and waste management practices, reveals considerable potential for both enhanced nature-based solutions and industrial use of biomass with carbon capture utilization and storage. In particular, programs of forest adaptation and climate smart forestry can increase forest resilience and resistance to wildfire and insect infestation. These programs will provide substantive and sustainable quantities of biomass that can be used as a feedstock to negative emissions industrial processes. Over time, active management of forests to adapt to climate change will lead to an increase in standing timber, enable more carbon to be stored in long-lived solid wood products, and generate a low-grade wood stream that can be used for bioenergy and direct biogenic carbon dioxide withdrawal.

Adapting Canada's Forests to a Changing Climate. Growing trees withdraw CO_2 from the air, release oxygen and deposit the carbon mostly as structural biomass in the trunk and branches and foliage. Healthy stands of growing trees are essential in maintaining the balance of atmospheric CO_2 emissions and withdrawal via natural systems. Anthropogenic (human activities) and naturally occurring disturbances, can have profound effects on the growth rate of trees and the capacity for atmospheric CO_2 withdrawal. Fluctuations in GHG flows from forested areas can be massive in scale and thus are important contributors to the mix of anthropogenic and natural processes that define the concentrations of CO_2 and other GHGs in the atmosphere.

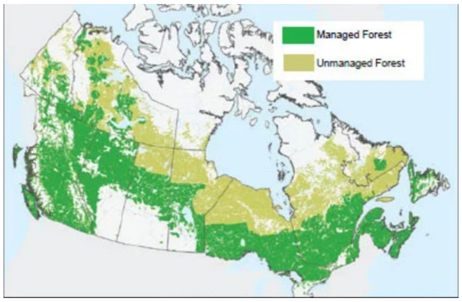


Figure 2. Managed and unmanaged forest area in Canada .

Canada has 347 million hectares or 9% of the world's forested land area (2). Sixty-five percent of this total area is under long-term forest management (figure 2). A full 39% of the world's certified sustainable forests are located in Canada. By law, forests that are harvested on public lands must be regenerated, and 77% of managed Crown forest land is certified to third-party standards of sustainable forest management (2). While the majority of Canada forests are defined as under management, a much smaller fraction of this forest area is subject to human activities.

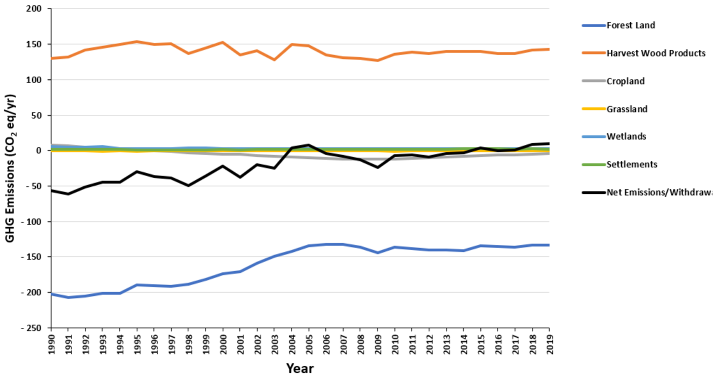


Figure 3. Historical Emissions/Withdrawals for Canada Reported to the IPCC under the Land Use Land-Use Change and Forestry category. The black line shows the net emissions/withdrawal as the sum of forest land management, harvest wood products, cropland, grassland, wetland and settlement subcategories. IPCC reported emissions under the LULUCF sector excludes GHG flows from managed forested that are not impacted by human activities. Data taken from Canada's GHG inventory (3).

Under the Intergovernmental Panel on Climate Change (IPCC) reporting rules, only GHG emissions and sinks from forested lands impacted by human activity are reported. These interventions include harvesting of forest products and active management to establish and maintain standing forests. Emissions and sinks from natural disturbances such as wildfires and insect infestations in forested areas outside of direct human impact are tracked but are not reported in the IPCC GHG inventory. Figure 3 shows historical GHG emissions/withdrawal from actively managed land in Canada as reported to the IPCC under the Land use, Land-Use Change and Forestry (LULUCF) category (3). The volume of harvested wood in 2018 (156 M cubic meters) was similar to that harvested in 1990 (4) and emissions from the harvesting of wood products have been relatively constant (130-140 Mt CO2eq/y) since 1990. From 1990 to 1998, atmospheric CO_2 withdrawal from actively managed forested areas more than offset emissions from harvesting wood products such that the LULUCF sector reported a net-negative emissions of about 50 million tonnes annually. Over the last 20 years, this balance has shifted dramatically with a considerable drop in atmospheric CO_2 withdrawal in forests under active management. In 2019, net emissions of 9.9 Mt of CO_2 equivalents were reported for Canada under the LULUCF category.

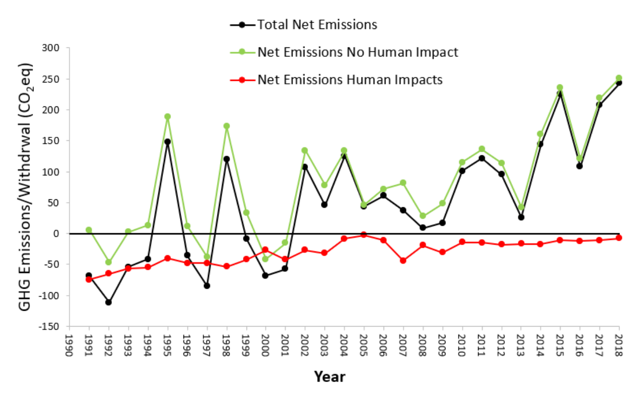


Figure 4. Historical Emissions/Withdrawals from Canada's Managed Forests (2). The black line shows the net emissions/withdrawal as the sum of emissions/withdrawal from actively managed lands (red line) and forest land without human intervention (green line). The recent increase in the severity and frequency of wildfires and insect infestation is driving the trend toward increasing emissions from Canada's forests. Data as reported by the National Research Council of Canada (2).

Net GHG emissions as reported to the IPCC for actively managed land areas in Canada provides an incomplete accounting of the total flows of GHGs. Emissions/withdrawals and the impacts of natural disturbances on forested areas outside of direct human intervention are tracked but not included in Canada's IPCC reported national GHG inventory.

Figure 4 summarizes the net GHG emissions/withdrawal from the entirety of Canada's managed forests as tracked by the National Research Council (2). Actual net emissions or withdrawals differ substantially from the anthropogenic emissions reported to the IPCC under the LULUCF sector. In 2018, a year of peak wildfire activity, net emissions reached 243 Mt of CO_2 equivalents. This magnitude of emissions, exceeded the total emissions from oil and gas extraction,

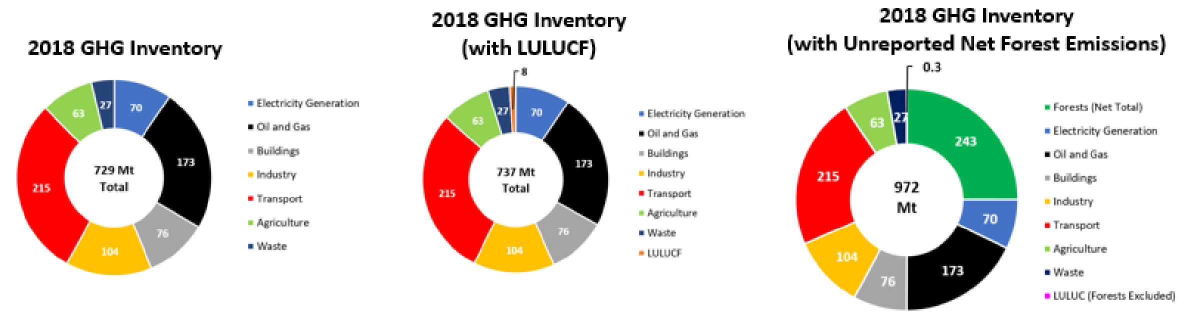


Figure 5. 2018 GHG emissions for Canada. The Land Use, Land Use Change and Forests (LULUCF) emissions are reported to the IPCC but are not included in Canada's GHG inventory. Emissions from forests without active human intervention are tracked but not reported to the IPCC. In 2018, emissions from forests driven primarily by wildfires were, by sector, the largest source of emissions in Canada and increased national emissions by 33% relative to the IPCC official GHG inventory .

petroleum refining, and fugitive emissions associated with oil and gas activities (3). Wildfires and insect infestations are the primary drivers of emissions from Canada's forests. These 'natural' disturbances show considerable annual variations and their impact on GHG emissions exceeds that of harvesting of wood products and active forest management. While naturally occurring wildfires are recognized as integral to the health and resilience of forests, it should be understood that the frequency and severity of wildfires has increased in recent years well beyond what can be considered as natural and beneficial. In recent years, wildfires have had devasting impacts on human settlements, GHG emissions and natural ecosystems. This trend is driven by droughts and heat waves associated with a changing climate. In the absence of adaptation and mitigation efforts, the severity and frequency of wildfires are projected to continually increase over the coming decades and triple or quadruple by 2100.

A program of sector-wide forest management to suppress wildfire and insect infestation is essential if Canada intends to effectively adapt to climate change and to achieve ambitious targets to cut GHG emissions. Forest treatments designed to reduce the likelihood and severity of wildfires consist of forest fuel removal and mechanical thinning. These treatments will remove large quantities of low-grade, high-risk biomass from treated areas. By removing undergrowth, established larger trees are relieved of competition which limits growth. The result over time is an increase in the volume of standing timber and thus an increase net atmospheric CO_2 withdrawal from forested areas.

California has an aspirational goal of treating 1 million acres of forests annually over a 20-year program of wildfire suppression and forest restoration (5). Modelling suggests that at a delivered selling price of $100 per tonne of dry biomass, 800,000 acres per year could be treated at a profit. The revenue from biomass sales would cover costs of extraction, chipping and hauling. Under this scenario, 15.1 Mt/y of dry biomass would be removed from California's forest and sold to end users (5). This biomass would be in addition to sawmill residues and accessible residues from shrublands. In total, with forest treatment programs in place, California's forests can provide 24 Mt/y of dry biomass on a sustainable basis from 2025 to 2045 (5).

In Sweden, 37% of the total energy consumed comes from biofuel (6). Forests provide the bulk of this bioenergy. Active management of forests in Sweden has led to a doubling of standing timber volumes since 1930 and this trend is projected to continue over the current decade (7). Net carbon withdrawal from forested areas is an important contributor to the 57% cut in national GHG emissions that has been achieved in Sweden since 1990 (8). Sweden has a per capita GHG emissions rate of 2.95 tCO_2e per person which is 7-fold less than that of Canada. On a per acre basis Sweden harvests 10x the quantity of timber relative to the harvest in Canada (7).

Active management of forests is not possible without a market for the low-grade biomass. In Sweden, this demand comes from extensive use of biomass for district heating and other industrial purposes. The increase in volume of carbon-sequestering standing timber in Sweden is driven by demand for low grade biomass.

In Canada, approximately 3.6 billion tonnes of CO_2 are released from forests with in-forest death and decay as by far the largest contributor (9). The J.D. Irving private timberlands in New Brunswick can be used to estimate the potential biomass yield from a national active forest management program. The sustainable harvest from these timberlands is 909,000 dry tonnes per year which on a per acre basis is 4-fold greater than the national average (10). When taking into account less productive regions, Canada could quite reasonably double the sustainable harvest rate under a national program. This would be consistent with the approaches taken in Finland and Sweden (11,12). Assuming no changes in volumes of solid wood products, about half of this total biomass would be available as residues. 100 Mt of dry forest biomass would have pulled 183 Mt of CO_2 from the atmosphere during the growth phase of the plants. This quantity approximates the current annual total emissions from the entire transportation sector in Canada (3). Using this biomass as a feedstock for industrial processes equipped with carbon capture and storage will result in the permanent isolation of the bulk of this CO_2 from the biosphere on a sustainable, annual basis. Forests treatments will increase the volume of standing timber and re-establish Canada's forests as a net carbon sink.

Agriculture Residues as a Biomass Resource. Agriculture and Agri-Food Canada estimates an average quantity of 48 Mt/y of available crop residues (13). Straws from the prairie provinces accounts for the majority of this biomass. These volumes are in excess of biomass required for the maintenance of soil health and for animal bedding. While the potential volumes of crop residues are substantial, there are considerable annual variations that are largely dependent on growing conditions in a given year. These fluctuations are problematic for industries such as electricity generation that are dependent upon reliable and consistent inputs. Potentially, the issue of variable volumes of residue straws can be managed by decentralized processing facilities (hubs) that would receive and process the biomass to produce durable, low moisture pellets suitable for long-term storage (14). Long-term storage can overcome the issue of variability in annual volumes of available residues. In addition to residues, there is considerable potential for an expansion of land use to include purpose grown energy crops such as short-rotation coppice tress (hybrid poplar and willow) and annual grasses.

Municipal Solid Waste (MSW) as a Biomass Resource. In Canada, an estimated 25 Mt of municipal solid waste are produced on an annual basis (13). This biomass is primarily committed to landfills. Anaerobic fermentation of waste materials in landfills releases methane as a potent GHG into the atmosphere. In 2019, based on global warming potential, the quantity of methane release from landfills in Canada equated to 26.7 Mt of CO_2 (3).

The Critical Role of Biomass Use with Carbon Capture and Storage in Climate Change Adaptation and Mitigation. If Canada intends to minimize the potential for future wildfire damage, ambitious programs of adaptive forest management must be undertaken. Given the vastness of the Canada's forests, adaptation to a changing climate will be an on-going process with massive annual removal of low-grade, high-risk biomass. Potentially, forest treatment could remove an additional 100 Mt tonnes per year of woody biomass with an energy content of 1.9 Exajoules (10). Ag residues and municipal solid wastes push the total potential supply of sustainably sourced dry biomass up to 173 Mt annually. The energy content of this volume of biomass is 70% of the energy of natural gas based on current consumptions rates in Canada. If all of this waste and residue biomass were to be used as a feedstock to industrial processes equipped with CCS, the net result would be removal of 180 Mt of atmospheric CO_2 per year. This volume of potential negative emissions approximates the total of current emissions from oil and gas sector activities in Canada, including refining and fugitive sources.

In the Net Zero 2050 scenario, the Canadian Energy Outlook 2021 forecasts a mix of Direct Air Capture (DAC) plus biomass use with carbon capture and storage. DAC is a costly, energy intensive process that is dependent upon an external supply of low (ideally zero) emissions energy. The World Resources Institutes indicates a range of costs between \$250-600 per tonne of CO_2 removal (15). There are serious barriers and uncertainties as to future cost reductions as the technology matures. In comparison, capture costs are estimated at $45 USD/t CO_2 for second generation CCS technology applied to an existing thermal power plant in Saskatchewan (16). In the CEO 2021 report (1), and in the roadmap for California to Net Zero (5), DAC enters the models when constraints limit biomass supply to lower cost negative emissions processes. In Canada, under the Net Zero 2050 scenario, withdrawals offset residual emissions, and industrial use of biomass with CCS accounts for 88% of the total negative emissions. 114 Mt of CO_2 withdrawal equates to projected limit of 109 Mt dry tonnes of available biomass.

In the CEO 2021 report, there is no mention of additional biomass supply coming from an expanded program of forest treatments. With this program in place, total sustainable annual volumes of residue biomass from all sources can readily meet the requirement for negative emissions under a Net Zero 2050 scenario while providing sufficient excess volumes to buffer inevitable inefficiencies or impracticalities in accessing 100% of the theoretical supply potential. DAC is unlikely to be required, if Canada implements an ambitious program of forest adaptation.

Biomass, Carbon Removal and Storage (BiCRS). The International Cool Earth Forum (17) defines BiCRS as encompassing all processes whereby:

1. Biomass is used to remove CO_2 from the atmosphere.
2. The carbon from use of this biomass is permanently stored underground as CO_2 or is embodied in long-life products.
3. The process does no damage to – and ideally promotes – food security, rural livelihoods, biodiversity conservation and other important values.

Sustainability is core to negative emissions industrial biomass use that does no damage. Biomass collection or harvesting cannot negatively impact food and feed production, damage natural habits and forest ecosystems, or slow the transition away from fossil fuels. Biomass use should focus on collection of residues from agriculture and forestry/forest treatments and municipal solids waste. There may be opportunities for purpose grown biomass, but land use must be managed to minimize impacts (within well defined acceptable limits) on food/feed production and natural forested areas.

Industrial negative emissions biomass processes include combustion for production of heat and/or generation of electricity, and conversion to secondary energy carries such as hydrogen. In process, the biomass carbon reacts with oxygen and the CO_2 is captured and permanently stored in geological formations. In addition, the potential exists to embed the captured carbon in long-life products.

Bioenergy with Carbon Capture and Storage (BECCS). BECCS can be considered as a subcategory of BiCRS and generally refers to combustion of biomass for heat and/or generation of electricity with CCS.

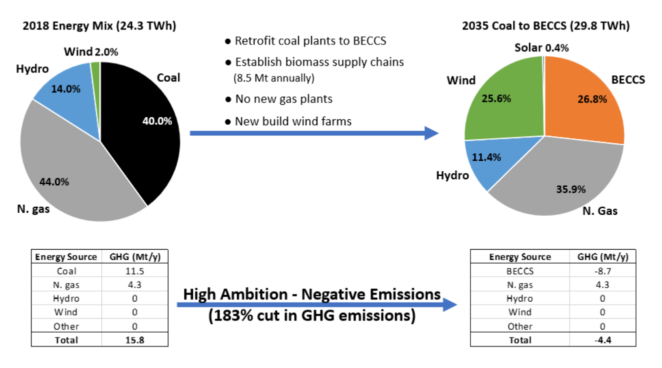
Electrification of practices across economic sectors is common to all Net Zero pathways. The CEO 2021 report forecasts a doubling of electricity supply by 2050 to meet increased demand coming from the transportation, buildings, and industry sectors of Canada (1). Canada's Energy Regulator anticipates a 42% increase in electricity generation by mid-century under the Net Zero Base Scenario for electricity supply (18).

At the COP26 global conference, the Prime Minister of Canada stated that Canada's climate ambitions include transitioning electricity generation across the country to net zero emission by 2035. This level of ambition, coupled with a growing demand for clean electricity, has profound implications for

Saskatchewan, Alberta, and the Maritime provinces where fossil fuels currently account for a substantial portion of the energy mix used to generate electricity.

A retrofit of suitable existing coal-fired power plants to CCS with fuel switching to biomass would facilitate a timely, cost-effective transition to Net Zero emissions by 2035. Under a equivalency program whereby emissions/withdrawal from a group of facilities are pooled, negative emissions from BECCS power plants could be used to offset continued emissions from natural gas plants. This would avoid the costly alternative of early shut-down and stranding of existing assets. Based on proximity to the Western Canadian Sedimentary Basin for geological storage of captured carbon, BECCS plants would likely be concentrated in Alberta and Saskatchewan. However, there are options for geological storage in other regions of Canada that should not be overlooked.

Using Saskatchewan as an example, by 2035, a complete retrofit of existing coal plants to CCS with fuel switching to biomass, along with the planned expansion of wind farms, would transition electricity generation in the province from emitting 16 Mt/y of CO_2 to net atmospheric removal of over 4 Mt annually. Going forward to mid-century, unabatted natural gas plants would be shut down on an orderly basis with capacity replaced by a build out of zero emissions options plus additional new build BECCS plants. By mid-century a full transition of electricity generation in Saskatchewan to BECCS plus zero emissions options could see this subsector of the economy functioning to pull about 17 Mt/y of CO_2 from the atmophere. This would provide 13% of the total negative emissions required under the CEO 2021 Net Zero 2050 scenario. About 16 Mt per year of dry biomass would be sourced from forest and/or agriculture residues. Nationally, by mid-century a combination of retrofits of existing facilities and new build BECCS power plants along with a build out of zero emissions options and an orderly shut down of remaining unabated fossil fuel plants would complete the transtion of the electricity generation sector to atmospheric withdrawal of over 50 Mt of CO_2 on an annual and sustainable basis.



Energy Source	GHG (Mt/y)
Coal	11.5
N. gas	4.3
Hydro	0
Wind	0
Other	0
Total	**15.8**

Energy Source	GHG (Mt/y)
BECCS	-8.7
N. gas	4.3
Hydro	0
Wind	0
Other	0
Total	**-4.4**

Figure 6. Potential Year 2035, Coal to BECCS plus Renewables Transition of Electricity Generation in Saskatchewan. Under a net-zero equivalency agreement, negative emissions from BECCS power plants would offset emissions from continued operation of natural gas plants and avoid early shut down and costly stranded assets.

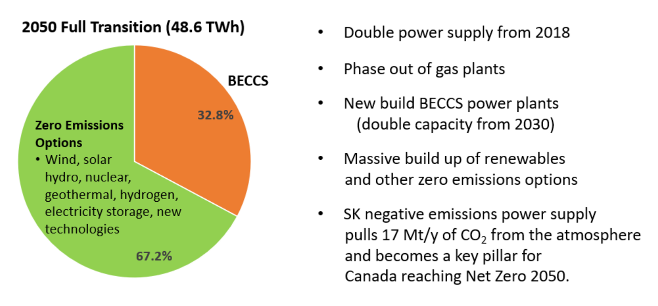


Figure 7. Potential Year 2050, Complete Transition of Electricity Generation in Saskatchewan.

Outside of Canada, projects are underway to retrofit existing coal-fired power plants to biomass with CCS. Recently, the large Drax Power Station in North Yorkshire England completed the process of fuel switching from coal to biomass. The station has a biomass electricity generation capacity of 2.6 GW (19).

In 2024, Drax will begin a retrofit of two 600 MW units to CCS. The biomass fuel used in the converted power plants consists primarily of wood pellets imported from Canada and the US. Recently, Drax purchased Pinnacle Resources which is the largest producer of wood pellets in Canada. By 2030, the Drax UK power plant will remove 8 Mt/y of CO_2 from the atmosphere (20). Negative emissions biomass use with CCS is an important component of the UK plan to transition to Net Zero emissions by mid-century.

Recently, Chevron, Microsoft and Schlumberger New Energy announced plans for a collaborative negative emissions BECCS project in Central Valley California (21). The facility will use locally sourced, agriculture residues as the energy input that is converted to synthetic gas for combustion to generate electricity with CCS. This initial power plant is modest in size (300,000 tonnes/y of CO_2 removal) but the collaboration envisions a portfolio of scaled up BECCS projects in suitable markets in the U.S.

Biomass Use for Hydrogen Production and Other Industrial Uses with CCS. The CEO 2021 Net Zero 2050 scenario forecasts that implementation of biomass use for hydrogen production with CCS will initially lag behind that of BECCS but by mid-century will provide similar magnitudes of CO_2 withdrawal (1). BiCRS hydrogen facilities would tend to be concentrated in Saskatchewan and Alberta based on ready access to geological storage and biomass supply corridors. There are multiple viable technologies for industrial biomass processing with CCS such as gasification to hydrogen and liquid fuels; fast pyrolysis to hydrogen, liquid fuels and biochar; and hydrothermal liquification to liquid fuels and biochar (4). While hydrogen production will likely dominate, other industrial uses of biomass with CCS may evolve over time.

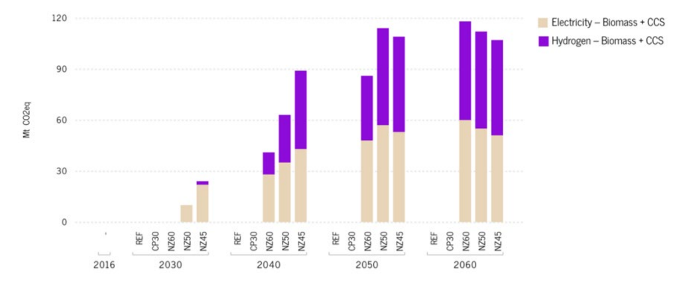


Figure 8. Scenario Forecasts for Negative Emissions Industrial Biomass Use with Carbon Capture and Storge. Biomass constraints limit implementation and atmospheric CO2 withdrawal potential. Reproduced with permission from the Horizon 2060 Canadian Energy Outlook 2021.

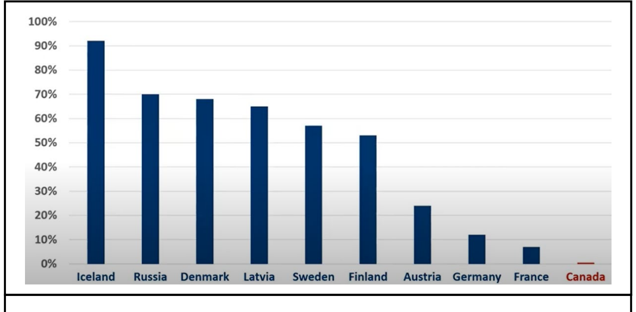


Figure 9. Percent of Northern Country Populations Served by District Energy Systems. Reproduced with permission from Torchlight Bioresources.

Biomass use for Negative Emissions District Heating. Canada can be considered an outlier among northern cold climate developed countries when it comes to the use of district energy systems (DES) for building heating and cooling. In Canada, DES is restricted to smaller, mostly institutional installations, whereas in Iceland, Russia, and Nordic countries, entire cities and the majority of the population are seviced by DES (22). With DES, a central heating/cooling plant produces steam or hot/cold water that is provided to buildings via a network of pipes. The energy is transferred to the building by heat exchangers and used for space heating/cooling and hot water. Combined heat and power plants integrate heat and electricity production. DES can be fueled by natural gas or, increasingly, biomass. Often the biomass used by DES plants consists of locally sourced munipal solid wastes that would otherwise be directed to landfills. Many northern countries in Europe have eliminated landfills (and the associated GHG emissions) and completed the transition to use of municipal solid wastes for energy and and other purposes (23).

About 85% percent of buildings in Stockholm Sweden are on a DES (24). The system is massive and contains 350 km of transmissions pipes and 2,800 km of distribution pipes. The combined heat and power plant is fueled by wood chips and municiple solid wastes. The Stockholm energy system is planning a full scale retrofit of the biomass plant to negative emissions carbon capture and storage.

Given Canada's residue biomass resource potential, there are obvious opportunities for large scale implementation of DES. In some established municipalities, existing natural gas lines would need to be replaced by DES infrastructure. The emissions abatement potential of this transition is sustantial and is based on replacing emissions intensive point source natural gas home heating with district energy supplied by negative emissions heat or heat and power plants fueled by biomass with CCS. Use of locally sourced municiple solids wastes could eliminate landfills and associated emissions.

Economics of Biomass Use with CCS. Carbon pricing will be essiential for cost-effective implementation of BiCRS. Negative emissions facilities would be paid per tonne of atmospheric CO_2 withdrawal and this payment could mirror the emissions tax applied to consumer use of fossil fuel products. Figure 10 shows the impact of carbon pricing on the levelized cost of electricity for three options of comparable sized thermal power plants. Under the proposed federal system, carbon pricing escalates to $170/t by 2030. Direct application of this price to emissions from a new build natural gas combined cycle power plant would double the levelized cost of electricity. In comparison, carbon pricing would result in a small increase in electricity costs for a CCS retrofitted plant with continued use of coal (low emissions). In the absence of carbon pricing, the high cost of BC wood pellets drives up the cost of electricity coming from a CCS retrofitted thermal power plant. However, if the utility is paid $70 per tonne of CO_2 withdrawn from the atmosphere, the cost of electricity is comparable to other options. At higher carbon prices, retrofit of an existing coal-fired power plant to CCS with fuel switching to biomass generates cost-advantageous electricity. Potentially, production credits can be used to control costs such that consumers and industry can be supplied with low-cost negative emissions electricity.

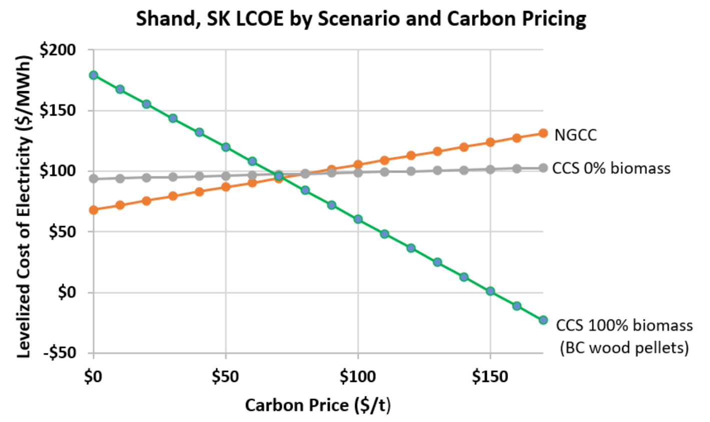


Figure 10. Levelized Cost of Electricity (LCOE) of 3 similar sized power plant options for the SaskPower Shand facility. LCOE calculator kindly provided as a personal communication by Dr. Brett Dolter (University of Regina). Calculator was based on the Shand feasibility study completed by the International CCS Knowledge Center for retrofitting the Shand thermal power plant to second generation CCS (14). Grey line shows the impact of carbon pricing on the LCOE of the converted plant with continued use of coal. Orange line show LCOE of similar sized new build natural gas combined cycle plant. Green lines show the LCOE with a negative emissions CCS retrofit of Shand and 100% fuel switching to BC wood pellets. Delivered cost of wood pellets set to $9.47/GJ (23). This option assumes the utility is paid the equivalent of the carbon price for atmospheric CO_2 withdrawal.

Similar pricing considerations will apply to hydrogen production from biomass with CCS and negative emissions biomass fueled district heat and energy facilities. Biomass transportation cost will be dependent on location and proximity of supply. In California, the cost of hydrogen production through combustion of forest management or agriculture residues was estimated at $64 USD/t of atmospheric CO_2 withdrawal (4). Similar to the situation with electricity production, in Canada, negative emissions revenue at $170/t of CO_2 plus the commercial value of the hydrogen produced can readily cover the costs of biomass procurement and carbon capture and storage.

In a well designed program of offsets, airlines and other industries without obvious or cost-effective alternatives to cut emissions could purchase carbon credits from negative emissions biomass facilities. BiCRS facilites could partcipate as sellers of carbon credits in cap and trade systems. A portion of the revenues collected from carbon pricing systems already in place in Canada could be funneled to negative emission facilities on a per tonne of atmospheric CO_2 withdrawal basis. The societal value of negative emissions in the global effort to combat climate change is considerable and thus can provide the economic basis for implementation.

Overview and Conclusions. Figure 11 provides an overview of a potential mid-century net zero emissions circular carbon economy. After implementation of all practical abatements across economic sectors, sizable GHG emissions remain from agriculture and the sum of niche sources. Modeling of Net Zero pathways estimates total residual emissions in the order of 130 Mt of CO_2 equivalent per year. During the growth stage of plants in forest and agricultural areas, CO_2 is absorbed from the atmosphere. Programs of adaptive forest management to suppress wildfires and insect infestation will lead over time lead to an increase in standing timber and net atmopheric CO_2 withdrawal. However, the magnitude of forest-based solutions will be well short of what is required to offset residual emissions. Low-grade, high risk biomass removed from forests under forest management programs will be additive to residues from harvesting of wood products, agriculture residues and municipal solid wastes. This large, sustainably sourced, volume of residue biomass can be used as a feedstock to negative emissions CCS equipped industrial processes of electricity generation, hydrogen production and district engergy systems. Captured carbon dioxide is permantely isolated from the biosphere through geological storage or embodiment in long-life products. Under a Net Zero 2050 scenario, by mid-century the combination of net CO_2 withdrawal by forests plus industrial biomass use with CCS offsets residual emissions.

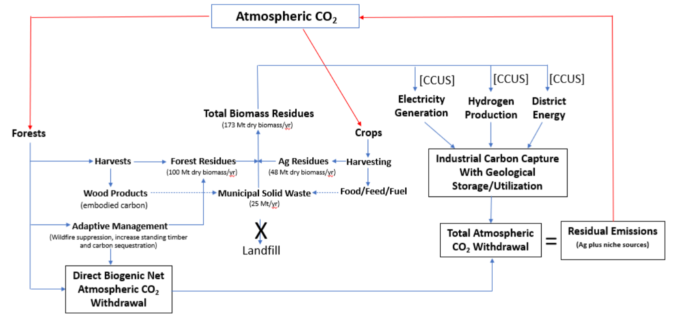


Figure 11. The critical role of forest adaptation, biomass use, and industrial carbon capture and storage/utilization to offset residual emissions under a net zero emissions scenario in 2050.

If Canada is to meet its 2030 targets for cutting emissions and build the net zero economy of the future, forest adaptation to a changing climate must be integrated with climate change mitigation efforts. Negative emissions industrial processes using biomass feedstocks with carbon capture and storage will be critical to a successful transition and should be given due priorty in policy development and allocation of funds.

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