Minimum Cost Strategies for GHG Mitigation for Ontario to 2030, and to 2050

Prepared for the

Environmental Commissioner of Ontario

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Environmental Commissioner of Ontario
Your Environment, Your Rights

SCMS Global

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1 Introduction

The Environmental Commissioner of Ontario (ECO) is an independent officer of the Ontario Legislature. One of the ECO's responsibilities, mandated under the *Environmental Bill of Rights, 1993*, is to report annually on progress of activities in Ontario to reduce greenhouse gas (GHG) emissions. The ECO's 2018 Greenhouse Gas Progress Report *Climate policy in Ontario: what's next?* describes why Ontario needs a new climate policy and provides guidance as to what this policy should include.

As support for this Report, the Office of the Environmental Commissioner engaged SCMS Global to carry out a special study for deriving minimum cost pathways, and reporting on status, priorities and essential actions, for Ontario to deliver necessary reductions in GHG emissions for 2030 and 2050. This study was carried out by a consortium, led by SCMS Global, and including ESMIA Consultants and Mr. Ken Ogilvie.

This study was carried out with the aid of a mathematical optimization model for deriving minimum cost pathways for all of Canada, and for each of its thirteen provincial and territorial jurisdictions. The pathways were derived for meeting both growing demands for an expanding economy, and for satisfying progressively more stringent GHG mitigation requirements. The opportunities for mitigation included comprehensive ranges of technology options, with associated costs, for every sector, in every jurisdiction, that produced GHG emissions. The model derived the minimum present worth cost for all of Canada, for the cumulative period to 2050, to meet declared national (e.g., Paris Accord) and provincial mitigation targets. The model also derived corresponding time varying combinations of strategic decisions and associated priorities for the respective jurisdictions, including Ontario, consistent with this minimum cost goal.

This study includes an opening section on the status of GHG mitigation in Ontario, and provides context for the challenge of meeting declared GHG emissions reduction targets in 2030, and in 2050. The approach and methodology is then described, followed by an overview of the principal source of information and premises used in this study. The results are then presented for the respective sectors that produce or consume GHG emissions. The final section includes conclusions and recommendations.

2 Ontario's GHG Emissions Profile

The most comprehensive source of information for GHG emissions, for Canada and for the thirteen provincial and territorial jurisdictions, is the National Inventory Report (NIR), produced and submitted annually, as per Canada's obligation as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC). Canada has produced an annual report for every year since 1990. The most recent report was for 2016.

Canada's GHG emissions increased from 603 million tonnes (Mt) of CO2 equivalent (CO2 eq.)[1] in 1990, to 745 Mt in 2007, and have since declined to 704 Mt in 2016. During this same period, Ontario's emissions increased from 179 Mt in 1990 to 206 Mt in 2003, and have also since declined to 161 Mt in 2016. Emissions in 2005, as the reference date in the Paris Accord, were 732 Mt and 205 Mt, for Canada and Ontario, respectively. In 2016, Ontario produced 23% of Canada's GHG emissions, second only to Alberta.

GHG emissions are grouped into three categories: combustion emissions, non-combustion emissions and land use changes (Figures 1 to 4 show emissions for Canada and Ontario, respectively, for 2016, and for 2005). The categories used to group emissions are slightly different than those used in the ECO's Greenhouse Gas Progress Reports, although the underlying data source is the same.

2.1 Combustion emissions

Combustion emissions are associated directly with the burning of fossil fuels and its derivatives (gasoline, diesel fuel, etc.). Such emissions include emissions for energy *production and delivery*, and for energy *consumption* (end uses). *Production and delivery* emissions includes all activities for production and delivery of energy commodities (fossil fuels and its derivatives, biomass/ biofuels, and electricity), including exploration, extraction, collection, refining, upgrading, transmission, generation, distribution and delivery to location of final use, or for export. In Figures 1 to 4, these are represented as *fossil fuel production* and *electricity production*.

Consumption emissions are from direct burning to meet specific end uses, such as burning natural gas for space heating and hot water & steam production in buildings, or combustion of gasoline for motive power. The end uses are represented by five end use sectors in Figures 1 to 4, including transport, industrial, residential, commercial, and agriculture.

It is important to note that most combustion emissions are from energy *consumption*. For Canada, in 2016, consumption emissions represented 43% of total emissions, while the entire production and delivery *supply chain* for fossil fuels and electricity represented only 30% of total emissions (Figure 1). For Ontario, in 2016, these differences were more dramatic, with consumption

1 GHG emissions include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride. The effects of GHG emissions, other than CO2, are converted into CO2 equivalent, based on the Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4) estimate of each compound's equivalent global warming potential over 100 years. For Canada, in 2016, emissions (reported in Mt CO_2 equivalent) were: CO2 558 MT (79%); methane (CH4) 99.8 Mt (14%); nitrous oxide (N2O) 37.1 Mt (5%), and other emissions collectively 13.2 Mt (2%). For Ontario, the corresponding numbers, in 2016, for CO2, CH4, N2O, and others, were 136 Mt (84.5%), 12.5 Mt (7.8%), 7.7 Mt (4.8%) and 4.8 Mt (3%), respectively.

representing 67%, while production and delivery represented only 7% (10:1 ratio) (Figure 2). This low value for Ontario arises as its electricity system is largely decarbonized, and its fossil fuel supply system (dominantly refineries) is not a major source of emissions.

2.2 Non-combustion emissions

Non-combustion emissions include emissions from four sources:

1. Industrial process emissions include emissions dominantly from chemical processes, with GHG gases being emitted as process by-products. Such emissions include conversion of carbonaceous material (such as CO2 release from conversion of limestone to lime for cement production), oxidation of carbonaceous materials, electrolysis, and various other processes.
2. Fugitive emissions includes emissions from oil and gas production, processing, oil sands mining, bitumen extraction, in-situ bitumen production, heavy oil/bitumen upgrading, petroleum refining, and natural gas transmission and distribution facilities. These emissions, dominantly methane, occur primarily as leakage or as direct venting from such facilities.
3. The agriculture sector produces non-combustion emissions, which are dominated by nitrous oxide from the application of nitrogen based fertilizers and from crop residue decomposition, as well as from enteric fermentation due to gastro-intestinal releases of methane from ruminant animals, especially cattle.
4. The waste sector includes emissions from treatment and disposal of wastes. Sources include solid waste disposal on land (landfill sites), wastewater treatment, and waste incineration. The dominant emissions are methane emissions from municipal landfill sites.

2.3 Land use changes

The third category is land use changes. In reporting to the UNFCCC, this category is designated as land use, land use changes and forestry (LULUCF). This is an important category as it normally represents a net sink for CO2 emissions. This category includes net effects of afforestation, improved forest management, carbon retention in long-lived forest products (such as timber construction for buildings), biomass for production of biofuels and electricity generation, biochemical production, and improved agriculture tillage for greater carbon retention in soils. It is important to note that this category includes only anthropogenic (human induced) impacts.

For 2016, the reported net sink for the LULUCF category for all of Canada was 28 Mt. There is no official reporting to the UNFCCC of the breakdown of this category for the respective provinces and territories. However, it is the intent that such reporting will begin within a few years. It is also noteworthy that in Canada's NIR 2018 Executive Summary Report, it was reported that "in 2016, this net flux amounted to 28 Mt, which, if included, would decrease total Canadian GHG emissions by 3.9%".

It is noted here that Ontario has been a proactive participant in developing strategies for this category as a growing significant GHG net sink for the Province and for Canada, for the long term.

2.4 Setting and challenge for Ontario

At the start of this study, Ontario had the *Climate Change Mitigation and Low-carbon Economy Act* in place, which had come into effect in 2016. The Act included the following GHG mitigation targets:

- Reduction of GHG emissions by 37% by 2030, relative to 1990; corresponding to 113 Mt in 2030 (actual in 1990 was 179 Mt).
- Reduction of GHG emissions by 80% by 2050, relative to 1990; corresponding to 36 Mt in 2050.

In addition, Ontario had also agreed, with the other 12 provinces and territories (Vancouver Declaration on Clean Growth and Climate Change (March, 2016)) to work on the *Pan-Canadian Framework on Clean Growth and Climate Change* to meet or exceed Canada's international mitigation targets. At the time of this Declaration, Canada was already a signatory to the Paris Accord (COP 21), with a commitment to reduce its GHG emissions by 30% below 2005, by 2030. At the subsequent COP 22 meeting in Marrakech, Canada presented a strategic plan for reducing its GHG emissions by 70 to 90% by 2050, again relative to 2005.

For the five-year period from 2011 to 2016, Ontario's emissions declined from 172 Mt to 161 Mt, representing an average annual reduction rate of 2.2 Mt. It is noteworthy that the most significant GHG reduction achieved during this period was for the *electricity production* category, reflecting the mitigation effects of the coal phase-out program in Ontario. For the other categories, net GHG reductions were minor, with GHG increases that would have occurred from higher energy demands in a growing population and expanding economy offset by GHG reductions resulting from other actions, including especially energy conservation and energy efficiency.

Figure 1. GHG emissions by sector for Canada – 704 Mt in 2016

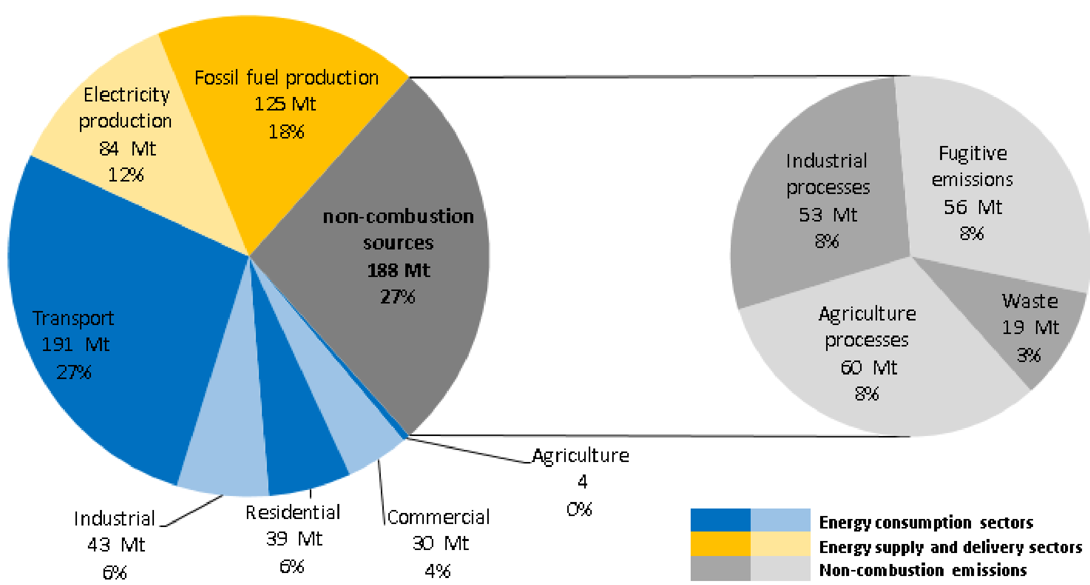


Figure 2. GHG emissions by sector for Ontario – 161 Mt in 2016

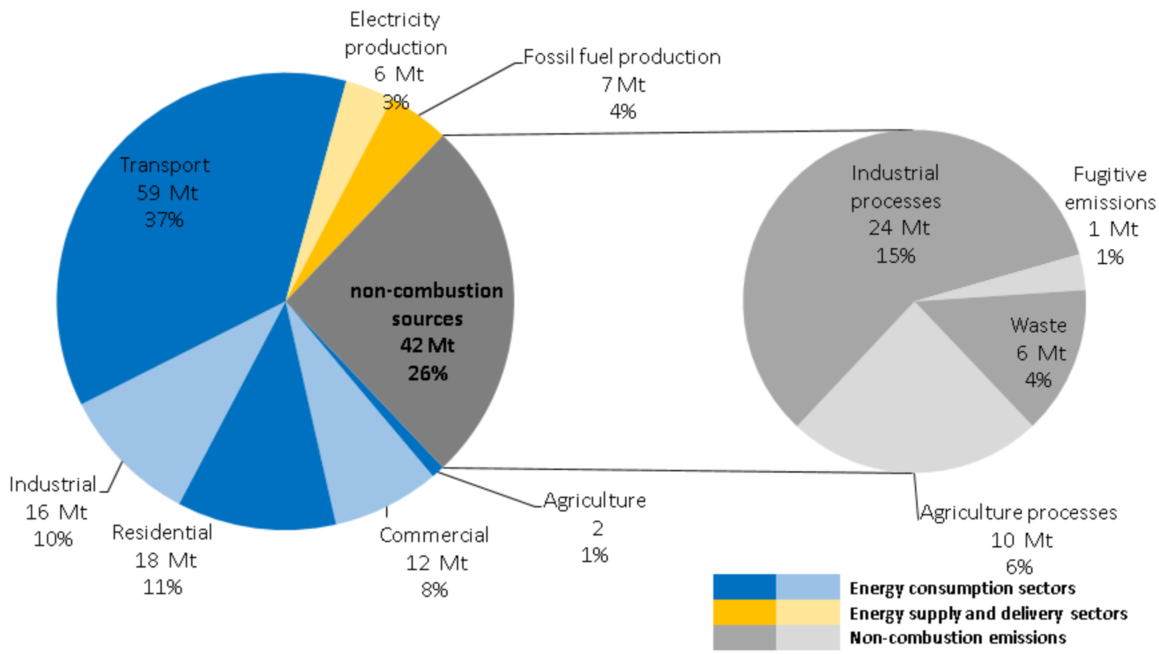


Figure 3. GHG emissions by sector for Canada – 732 Mt in 2005

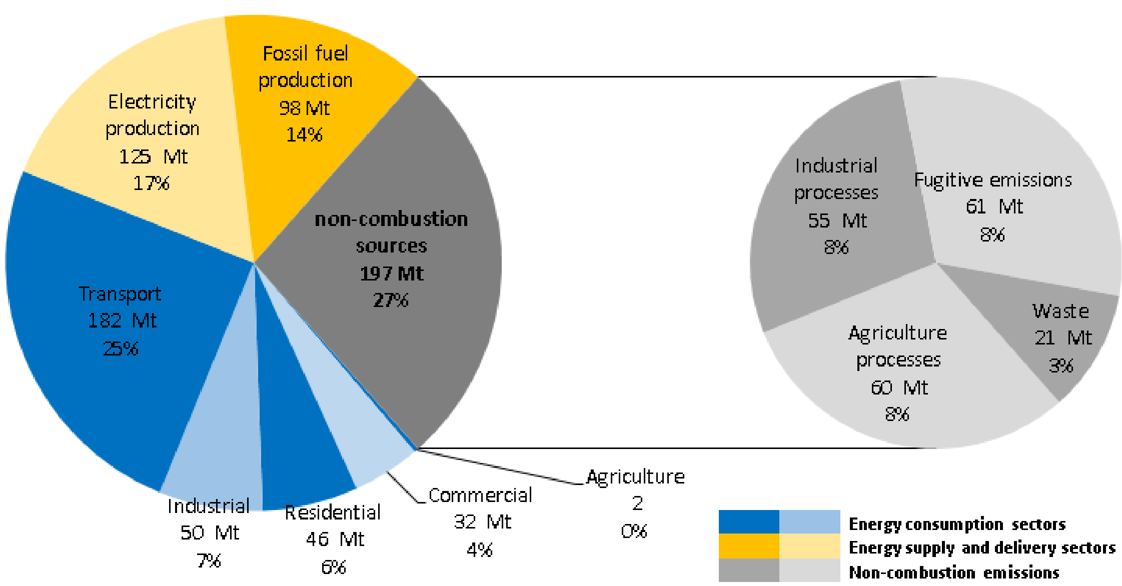
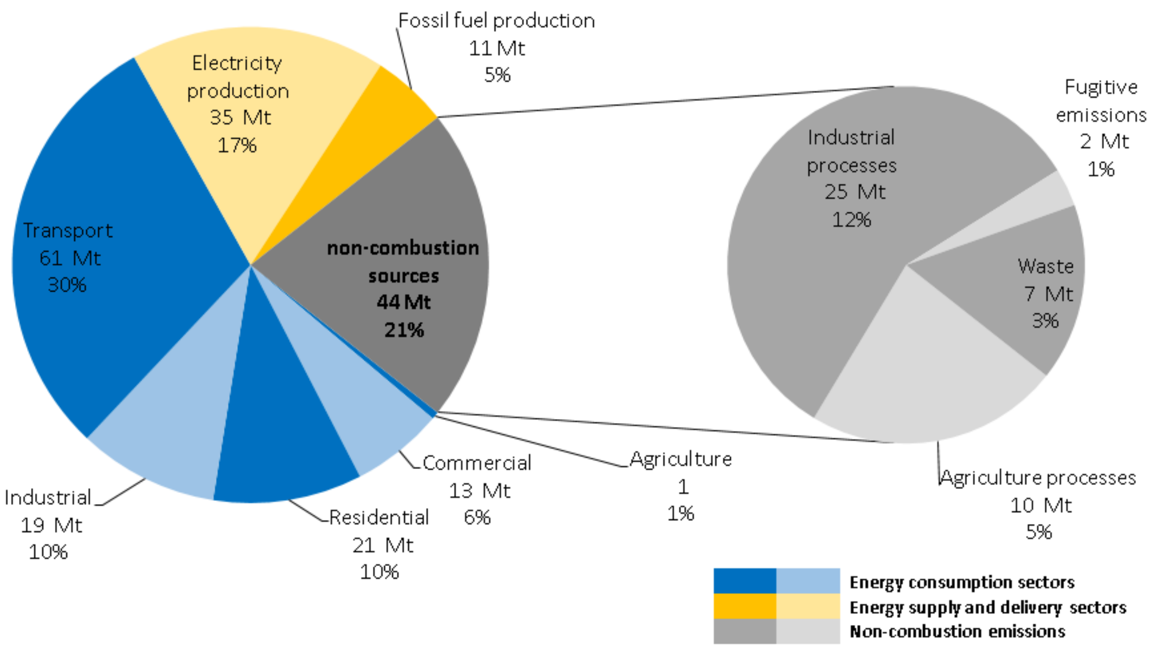


Figure 4. GHG emissions by sector for Ontario – 205 Mt in 2005



For Ontario to achieve its previously declared GHG mitigation target of 113 Mt in 2030 (37% below 1990), it would need to achieve an average reduction rate of 3.4 Mt per annum for the 14 year period from 2016 to 2030. For the period, 2030 to 2050, this rate would need to increase even further, to almost 4 Mt per annum, to meet the 2050 target of 36 Mt (80% below 1990).

These high reduction rates for GHG mitigation present a significant challenge, especially for Ontario (Figures 1 to 4).

- As noted above, the dominant category for GHG mitigation has been *electricity production*. At this stage, there is limited potential for further mitigation in this category in Ontario, as the coal phase out program is essentially complete (see reduction in GHG emissions for electricity production from 17% of Ontario's overall emissions in 2005 to 3% in 2016, from comparison of Figures 4 and 2).
- With respect to mitigating non-combustion emissions, there are serious challenges with achieving substantial early progress, especially for industrial process emissions and agriculture emissions.
- When considering major reductions in combustion emissions in Ontario, the dominant focus has to be on transforming end uses (energy *consumption*) away from reliance on fossil fuels. The greatest end use opportunities are in the transport, buildings (residential and commercial) and industrial sectors, as shown in Figure 2.

From the foregoing, it is clear that a well-defined GHG emissions reduction plan is essential. Such a plan should serve to define the fundamental transformations that are required, including changes in the various supply and end use sectors, transformations of energy systems, potential benefits from inter-jurisdictional cooperation, technology changes, strategic priorities, supporting policies and early actions. A good place to start is to identify pathways that are economically efficient and consistent with a minimum present worth cost objective for satisfying both continuing economic growth and progressive GHG mitigation.

In response to this situation, the Consortium carried out comprehensive analytical assessments for defining minimum cost pathways for Ontario. The assessments were based on a specialized approach, including application of optimization modelling methodology. This approach and related methodology were used to define pathways for meeting designated GHG mitigation targets for both 2030 and 2050 for Ontario, within an overall Canadian context.

During the course of this study, the Government of Ontario introduced a Bill that, if passed, would repeal the 2016 *Climate Change Mitigation and Low-carbon Economy Act*. However, the government has stated its commitment to climate change mitigation, strong economic development and high value employment. As a guiding premise for this study, it was assumed that the Province of Ontario remains committed with the other provinces and territories across Canada to support Canada's international obligations, as defined in the 2016 Vancouver Declaration on Clean Growth and Climate Change.

3 Goals for this Study

This study had two goals:

1. To derive and report on minimum cost pathways for Ontario to achieve GHG mitigation targets for both 2030 and 2050. This includes Ontario's optimum contribution for Canada to achieve 30% and 80% reductions in GHG emissions in 2030 and 2050, relative to 2005, at minimum cost for all of Canada. In addition, Ontario had additional more stringent targets, which are embodied in the *Climate Change Mitigation and Low-carbon Economy Act,* of 37% and 80% reductions in emissions by 2030 and 2050, relative to 1990. Analyses were carried out, both with and without these additional Ontario targets.
2. To provide insight on the most important mitigation measures that should be considered as high priority candidates for meeting GHG mitigation targets for 2030, and for meeting longer term mitigation targets for 2050 and beyond.

4 Approach and Methodology

As noted above, there is a need to define the minimum cost pathway for achieving GHG mitigation targets, while supporting economic development and growth and the creation of high-value jobs.

The derivation of a minimum cost pathway for Canada, and for each of its 13 jurisdictions, is complex. It requires comprehensive consideration of all sectors in all Provinces and Territories that produce GHG emissions, along with considering all options, with related costs, for achieving net reductions in emissions. It is also necessary to assess the effects of inter-connections between jurisdictions, as well as between individual Canadian jurisdictions and jurisdictions outside Canada (import or export). Because of the many different combinations of options, including variations over time, it was necessary to resort to a *systems methodology* approach, including application of *best in practice* optimization models, for systematic derivation of minimum present worth cost solutions.

Systems methodology is a problem-solving process, intended to provide better and more accurate understanding of the behaviour of complex systems The essence of the approach is to separate the overall system into a series of component elements, or sub-systems. The behaviour of the overall system is then defined mathematically, in terms of the combined behaviour of each of the sub-systems, as well as the behaviour of linkages between sub-systems. In the context of the study reported herein, a sub-system can be considered to be a specific sector, in a specific province or territory, and in a specific time period, which needs to fulfill prescribed demands. There are defined relationships which represent interactions with the same sector in other time periods, with other sectors in the same jurisdiction in the same time period, and with other sectors in other jurisdictions in the same time period. There can also be a prescribed goal(s) which defines desired results for the entire system, as well as for some or all of the sub-systems. For this study, the prescribed goal for each *scenario* was to derive minimum present worth solutions for all of Canada, and for its thirteen jurisdictions, for a series of time periods to 2050, to meet growing energy-based demands, as well as satisfying increasingly stringent GHG emissions reduction targets.

In Canada, the only currently commercially available optimization model, fully calibrated and tested, for GHG mitigation planning, is the Canadian portion of the North America TIMES Energy Model (NATEM-Canada), owned and operated by ESMIA Consultants. The formulation is based on The Integrated MARKAL-EFOM System (TIMES)[2] formulation, which is used for energy-climate change planning in up to 70 countries around the world. Its application and use is coordinated globally by the *International Energy Agency* through its *Energy Technology Systems Analysis Program* (IEA-ETSAP). This model was the core model used for deriving minimum cost solutions for all of Canada, and for each of its 13 jurisdictions, for achieving up to 80% reductions in GHG emissions by 2050, relative to 1990, for the Trottier Energy Futures Project (TEFP)[3].

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2 The TIMES model generator combines all the advanced features of its predecessors, such as the MARKAL (MARKet ALlocation) and the EFOM (Energy Flow Optimization Model) models, as well as new features developed over time.

3 TEFP - Trottier Energy Futures Project (2016). Canada’s Challenge & Opportunity - Transformations for Major Reductions in GHG Emissions.

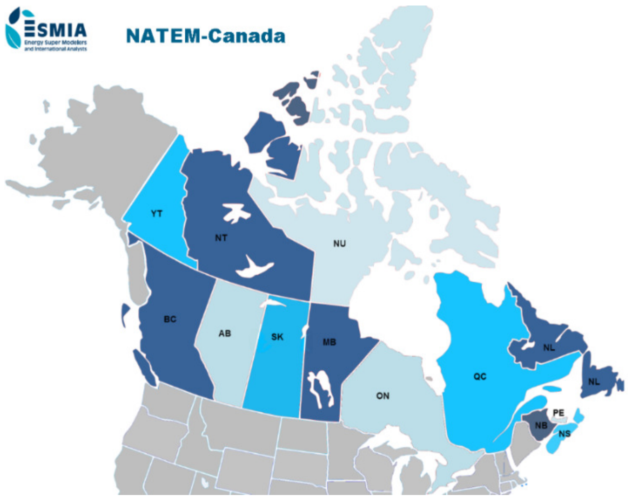
Subsequent to completing the TEFP, this model has been applied for other projects, dominantly in Quebec, and has been updated and further calibrated to be consistent with best available current information. This includes updated projected costs (such as declining costs for solar panels and wind turbines), fossil fuel price projections (updated using 2017 National Energy Board projections), national policies (such as the coal phase-out program), and an expanded range of mitigation options (such as natural gas-based generation with combined cycle, cogeneration and/or carbon capture and storage (CCS)). For TEFP, and for subsequent updates, such information has been adapted to be applicable for each respective jurisdiction (such as accounting for variations in capital costs for hydro developments in different jurisdictions).

TIMES-MARKAL models, such as the NATEM-Canada model, represent the entire energy-GHG mitigation system of a country or region, including either as single or multiple jurisdictions. Canada is represented by its thirteen provinces and territories (Figure 5).

As shown on Figure 6, the system representation includes extraction, transformation, distribution, end-uses, and trade of various energy forms and materials. Each stage is described by means of specific technologies characterized by economic and technological parameters. The model also tracks GHG and other air contaminant emissions from fuel combustion and processes. In baseline scenarios, end-use demands are exogenously specified in terms of socio-economic needs (e.g., transportation, expressed in passengers-kilometres) over a future time horizon. Such models use dynamic linear programming to derive minimum net total cost of the energy system, including investment costs, operating and maintenance costs, plus costs of imported fuels, minus incomes of exported fuels, minus the residual value of technologies at the end of the model horizon (in this study, residual value in 2050). The main model outputs are future investments and activities of technologies at each period of time. Important additional outputs of the model are the implicit price (shadow price) of each energy material and emission commodity, as well as the reduced cost of each technology (i.e., the cost reduction required to make a technology competitive).

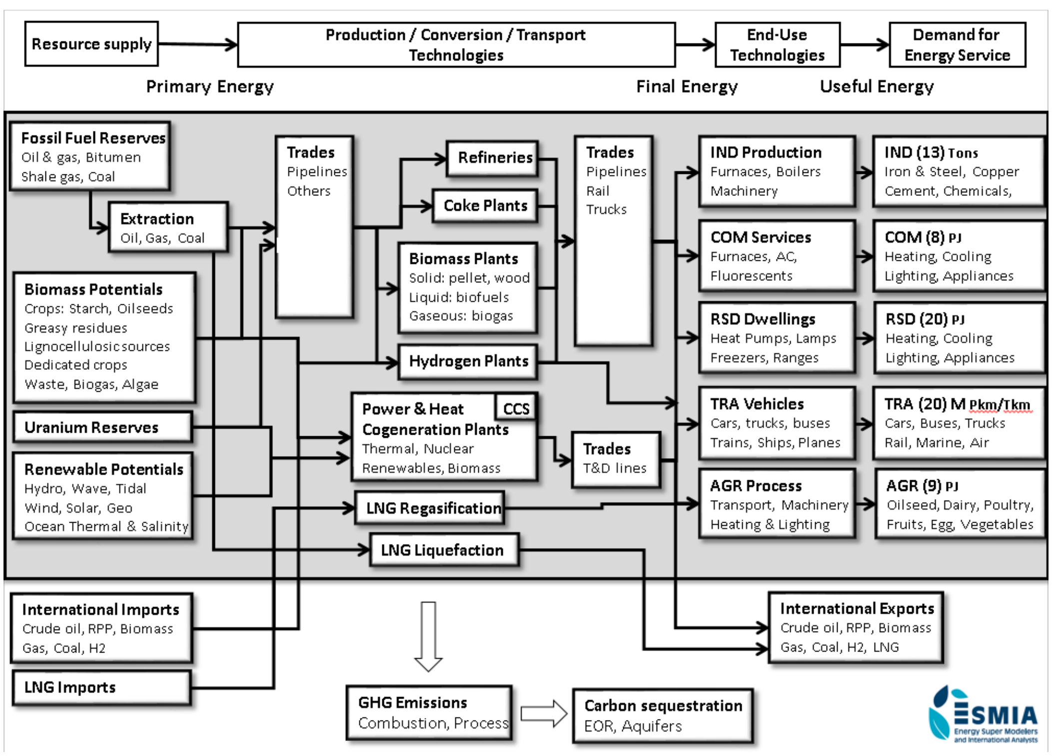
In GHG mitigation scenarios, emissions reductions are brought about by technology and fuel substitutions which lead to efficiency improvements and process changes, by carbon capture, use and sequestration, and by endogenous demand reductions.

Figure 5. Representation of provinces and territories in NATEM-Canada Model



Code	Province/Territory
AB	Alberta
BC	British Colombia
MB	Manitoba
NB	New Brunswick
NL	Newfoundland and Labrador
NS	Nova Scotia
NT	Northwest Territories
NU	Nunavut
ON	Ontario
PE	Prince Edward Island
QC	Quebec
SK	Saskatchewan
YT	Yukon

Figure 6. Summary representation of the energy system for each jurisdiction in Canada



For the current study, the approach was based on deriving minimum cost solutions for three separate scenarios.

1. The **first scenario** was a Reference (REF) scenario which was based on the premise that there would be no GHG targets, and no further action specifically for the purpose of GHG mitigation, and that future energy demands to 2050 would be satisfied by a minimum present worth cost for all of Canada. In this scenario, future levels of GHG emissions are not explicitly specified, but are reported as outputs from the model in response to increasing population and economic growth.
2. A **second scenario** (FED) was based on the premise that Canada would meet both its 2030 (30% below 2005) and 2050 (80% below 2005) GHG mitigation targets at minimum present worth cost for all of Canada. It is noted that actual results for respective jurisdictions, including Ontario, could be either above or below the national target, as opportunities and costs for emissions reduction will differ between jurisdictions.

   The computed model results (presented in Table 1 below) suggest, that for the least-cost pathway, Ontario's GHG reductions would be 36% and 75% below Ontario's 2005 levels, for 2030 and 2050, respectively. It is important to note that this approach does not take into account any equity considerations between provinces, and is based purely on a least cost solution for all of Canada.
3. A **third scenario** (FED+ON) was based on the premise that Canada would meet its 2030 (30% below 2005) and 2050 (80% below 2005) targets at minimum present worth cost for all of Canada (i.e., the same as the second scenario), and that Ontario would also meet its additional targets (37% below 1990 by 2030, and 80% below 1990, by 2050).

For all three scenarios, it was assumed that existing corporate average fuel efficiency (CAFE) standards (including agreed tighter standards in the future) and the federally mandated coal phase-out for electricity production would be implemented as planned, and minimum specified ratios of biofuels (ethanol and biodiesel) in gasoline and diesel fuel, respectively, would be maintained, but not expanded. The planned federally imposed national carbon pricing backstop program was assumed not to be implemented. It was assumed that provincial GHG mitigation targets (other than for Ontario in scenario 3) would also not be implemented.

The primary purpose of these scenarios was to assess minimum cost pathways to 2050 for Ontario to meet its GHG mitigation obligations within a comprehensive Canadian context. This was based on comparing results for the second and third scenarios against the first scenario, for establishing differential costs for GHG mitigation, and for determining the changes that would be required to achieve the committed GHG mitigation targets.

The scenarios were analyzed for combustion emissions only (Table 1). The reason for excluding non-combustion emissions was due to a general lack of well-defined options for reducing GHG emissions from such sources, as well as a lack of credible supporting information and data, including costs. Accordingly, assessment of the potential for reducing non-combustion emissions was qualitative, based on an updated literature review, including especially results of extensive reviews as reported in the IPCC Fifth Assessment Report. This was the approach adopted for the TEFP. There has been further model development work carried out since the submission of the TEFP in 2016, for representing non-combustion emissions. However, supporting data for such representations were considered by the consultants to be of inadequate quality.

Opportunities for developing net carbon sinks from land use changes, including forestry, were also excluded in the analyses. The opportunities for carbon sequestration are understood, and the importance of developing carbon sinks is recognized as being an essential strategy for Canada to deliver on its long term GHG mitigation targets. It is also recognized that such decisions need to be made early, especially as there are lengthy time lags between making investments in afforestation, improved forest management and the production of long lived forest products, and realization of the associated carbon sinks. As with non-combustion emissions, there is a need to strengthen supporting analytical processes and to have better information and data. There is also a need to develop and apply optimization modelling methodology for deriving minimum cost solutions for integrating land use changes with GHG mitigation.

It is important to note that target reductions as specified in the description of the scenarios for GHG emissions are for total emissions. An important premise for this study was that the reduction in combustion emissions would decrease by the same proportion as for total emissions. This was based on qualitative consideration of two opposing trends for non-combustion emissions and land use changes. Firstly, with non-combustion emissions, the same proportional reductions in emissions are unlikely, for reasons as noted above. On the other hand, land use changes, including forestry and agriculture, have the potential to be an increasing sink for carbon retention. It is not known at this time whether the combination of these two trends will result in the same proportional reductions as for total emissions; however, until better information is available, this premise was considered reasonable for defining target reductions for combustion emissions in the current study.

As noted above, target reductions for the total of combustion and non-combustion emissions for all of Canada are 30% and 80% below 2005, for 2030 and 2050, respectively. Perspectives on the challenge for major reductions in emissions, especially for Ontario, are as follows (Table 1):

- First of all, it is important to appreciate Ontario's position with respect to status on GHG mitigation within a Canadian context. For the period from 2005 to 2016, Ontario reduced its total emissions by 44 Mt, which represents a 21.5% reduction from 205 Mt in 2005. This included 42 Mt of reduced combustion emissions and 2 Mt of reduced non-combustion emissions. This large reduction has been dominated by results of the coal phase out program. This was the largest single source of emissions reduction in Canada during this period. In terms of percentage reduction in emissions, Ontario ranks third, behind Nova Scotia (33%) and New Brunswick (24%).

  In comparison, Canada has only reduced its total emissions, during this same period, by 20 Mt (3.8%), including 18 Mt of reduced combustion emissions and 2 Mt of reduced non-combustion emissions.

- When assessing additional GHG mitigation requirements for Ontario for the period from 2016 to 2030, there are different perspectives. Based on the very simplistic premise of simply reaching 30% reduction in 2030, the further reduction in GHG emissions would need to be 17.5 Mt, equivalent to 1.3 Mt per annum. In the FED scenario, however, it has been shown that the minimum cost solution for Canada would result in Ontario having to reduce its emissions in 2030, to 36% below 2005 (Table 1). This would correspond to 29.8 Mt, equivalent to 2.1 Mt per annum. When also considering the Ontario specific target of 37% below 1990 (179 Mt in 1990), the reduction from 2016 to 2030 would need to be 30.5 Mt, equivalent to 2.2 Mt per annum.

From these perspectives, the general guideline should be to target for more than 2 Mt per annum of GHG mitigation for the remaining period to 2030, with this being dominated by reductions in combustion emissions. For the period from 2030 to 2050, the rate of annual GHG mitigation for Ontario will need to further increase to about 4 Mt per annum, as Canada reduces its emissions from 30% to 80% below 2005, for 2030 and 2050, respectively.

- Notwithstanding Ontario's important contribution, from 2005 to 2016, to Canada's GHG mitigation commitment, there are significant challenges for Ontario to meet further required reductions to 2030. Virtually all of the reduction to date has been in the electricity production category, which are clearly associated with Ontario's coal phase-out program. There is limited additional mitigation potential for this category. Accordingly, reductions will need to occur in other sectors, especially in one or more of the consumption sectors, where there has been virtually no net GHG reduction in recent years.

  For the period from 2030 to 2050, it will be necessary to continue with additional aggressive mitigation programs, especially for the *consumption* sectors, while also benefitting from results of early developments for reducing non-combustion emissions and for developing carbon sinks with land use changes.

Table 1. Total and combustion emissions for Canada and Ontario

Mt (1)	1990	2005	2011	2015	2016	2030 (2)	2050 (2)
Canada							
Total emissions	603.0	732.0	700.0	714.0	704.0	512.4	146.4
Combustion emissions	432.0	534.0	518.0	524.0	516.0	373.8	106.8
Ontario							
Total emissions	179.0	205.0	172.0	163.0	161.0		
Combustion emissions	131.4	161.5	132.6	123.6	119.6		
FED+ON: Target on combustion emissions (3)						82.8	26.3
FED: Computed results for combustion emissions (4)						104.0	40.0
FED: Ontario's proportional share of national target for combustion emissions (5)						113.0	32.3

1. All numbers in this Table are based on information in the National Inventory Report for 2016, and excludes the LULUCF category

2. Maximum emissions for Canada in 2030 and 2050, respectively, are calculated as being 30% and 80% lower than actual total emissions in 2005. Maximum combustion emissions for Canada in 2030 and 2050, likewise, are calculated as being 30% and 80% lower than actual total combustion emissions in 2005.

3. The FED+ON targets for combustion emissions, for Ontario only, for 2030 and 2050, were 37% and 80% below 1990, respectively.

4. These are actual computed combustion emissions for Ontario, for 2030 and 2050, respectively, as derived in the FED scenario. These values are 36% and 75% below 2005 values, for 2030 and 2050, respectively.

5. These calculated FED numbers for Ontario represent 30% and 80% reductions in combustion emissions for Ontario, in 2030 and 2050, relative to 2005, respectively. These were not imposed in the FED scenario, but are included here, primarily for comparison with actual computed results of the FED scenario.

5 Premises, Information and Data

In this section, an overview is provided on the principal premises used for this study, as well as information and data used as input for the NATEM model.

As a general overview comment, it is important to note that there was extensive advance preparation carried out for the TEFP, before any model scenarios were analyzed. Most of the inputs for the model were documented in Working Papers, which were reviewed by the TEFP Expert Review Panel. In addition, reporting of detailed data used for the TEFP, is presented in Section 4 of the associated *Full Technical Report & Modelling Results* Report.

Since completing the TEFP in 2016, the NATEM model has been progressively updated and tested with new information from various authoritative sources. This is to ensure that system representations reflect the best currently available information, as well as longer term trends in performance characteristics and costs for various technology options. There has also been updating of macroeconomic trends and international prices for the various energy commodities.

It is also important to also note that, in the TEFP, special attention was given to carrying out comprehensive calibration of the NATEM model, before carrying out any model runs. This was especially important as this was the first time that the model had been applied as a commercially proven optimization model for deriving minimum cost solution for energy-GHG mitigation for all of Canada, and for its 13 respective jurisdictions.

5.1 Premises

The most important premises for the current study include the following:

- A fundamental premise for the TEFP and for this study was based on *no constraints assumptions*. There were no economic, social, socio-economic, environmental, regulatory, inter-jurisdictional or political constraints. It was also assumed that there were no excessive scheduling delays with infrastructure developments. This served to define the maximum possible potential, with existing available resources across Canada, to meet growing demands and to satisfy emissions reduction targets, at overall minimum cost.

  This was an important premise as it provided the basis for considering cost impacts for deviations from minimum cost solutions. Imposition of constraints and/or rejection of selected options from any derived minimum cost solution, can only result in increased minimum cost. This then provides the basis for directly assessing cost trade-offs for such impositions and/ or rejected options.

  It is recognized, of course, that there are valid justifications for deviating from a minimum cost solution. These include, as examples, satisfying different socio-economic, political or equity requirements, or valuation of co-benefits or costs (e.g., the non-climate environmental impacts of different energy choices). The value of this approach, therefore, is to provide more accurate evaluations of cost impacts for such considerations, based on comparing minimum system wide cost solutions, with and without such considerations.

- A special area of development for the TEFP was for credible representation of electricity supply options for meeting electricity demand. This is an area that has become more complex in recent years, with addition of intermittent renewables in the generation supply mix. The additional complexities are as follows:

- Intermittent renewables, including wind, solar, run of river hydro, instream and tidal generating options, produce electrical energy, but little dependable capacity. As a consequence, there is a need for other generating options, such as hydro (including additional capacity at existing hydro sites), nuclear, thermal and pumped storage, to provide this complementing dependable capacity
- There are *dispatch* limitations that constrain the total amount of generation available from intermittent renewable generating sources in any electricity supply system. These limitations are dependent on the composition of the supply mix. For systems that consist of only hydro and intermittent renewables, and no interconnections, the upper limit for generation from intermittent renewables is about 25% of total system electrical energy demand. This percentage can increase if there is cycling storage, such as pumped storage, for absorbing excess generation during low demand periods. This percentage may also decline if there is base load generation with limited cycling capacity (such as nuclear or base load thermal generation).
- There are additional complexities with interconnections, especially when including sale of dependable capacity. Most interconnection arrangements between neighboring jurisdictions in Canada provide for exchange of electrical energy by sequencing generating facilities based on next lowest variable operating cost. However, there may be additional opportunities for minimizing overall cost by also transferring a portion off dependable capacity responsibility to neighboring jurisdictions.

  In the TEFP, there were special analytical developments for considering these complexities. These were tested to reflect these and other considerations for ensuring that any electricity supply option in any jurisdiction in any time period satisfied electrical energy demand, dependable capacity demand, and dispatchability constraints. This is described in more detail in Sections 3.4.2 to 3.4.4 of the TEFP *Full Technical Report and Modelling Results* document.

- A related consideration with electricity supply planning was the cost impact on the high voltage transmission grid with increasing intermittent renewables generation. Grid investment and operating costs increase as the ratio of intermittent renewables increases. From literature review, it was established that incremental costs for the grid were 16% of incremental costs for generation supply. This allowed such costs to be appropriately reflected in the overall cost minimization process. This is described in more detail on Section 3.4.5 of the TEFP Full Technical Report and Modelling Results document.
- One of the important initiatives in the TEFP was to develop greater in-depth understanding of the potential and limitations for increased production and use of bioenergy to replace fossil fuels in meeting energy-based end uses. In early results from the scenarios, the use of biomass was projected to greatly increase. This resulted in a series of queries including availability of biomass feedstock, availability of land for increased production of energy crops, potential for significant changes in agricultural practices, and potential for specialty energy crops, for Canada, and the respective jurisdictions. Detailed assessments were carried out with a separate simulation model (CanESS), based on best available information and preliminary judgements. This served to define availability and limits of various bioenergy feedstocks. These values were then transferred to the NATEM model for deriving minimum cost solutions which satisfied resource limits on availability of various bioenergy feedstocks. This is

described in more detail in Section 3.4.8 of the TEFP Full Technical Report ad Modelling Results document.

5.2 Information and Data

There is extensive information and data included in Section 4 of the TEFP *Full Technical Report and Modelling Results* document. This was the dominant information base for the current study. However, there have been additions and modification to the TEFP database, as described below:

- For the TEFP, the base year was 2011. Information and data was based on best available information to 2013, which was then converted into equivalent 2011 dollars.

  Subsequent to completion and submission of the TEFP in 2016, there have been updates of the database for the NATEM model, up to 2015, to reflect the most significant technologic developments and associated costs for the period up to 2015. All such information has been converted into equivalent 2011 dollars.

- The analyses have been carried out on the basis of constant 2011 dollars, after eliminating effects of inflation. The selected discount rate for present worth analyses, for the cumulative period from 2015 to 2050, was 4%.

- In the TEFP, there were comprehensive analyses carried out for deriving the principal macroeconomic drivers. These included population growth, GDP/ capita, total GDP, and gross output for the various industrial sectors. Gross output was then disaggregated into gross output projections for each industrial sector, in each jurisdiction.

  For the current study, these projections were modified, based on updated information from the most recent report of the National Energy Board4. The principal results are shown on Table 2. The reported results include NEB projections to 2040, with extrapolations to 2050.

- Industrial gross outputs for the respective sectors in the different jurisdictions were modified to reflect changes in GDP projections for the current study, relative to values in the TEFP. This was normally based on direct proportioning to values used in the TEFP.

- All other end-uses demands for energy services were projected to 2050 in a consistent manner with these most recent macroeconomic drivers.

- Other important macroeconomic drivers included projected global prices for fossil fuels, especially oil and natural gas. These are also presented in Table 2. These were the values used for determining optimum levels for production and export of these commodities, while also being consistent with achieving overall cost minimization for GHG mitigation in Canada.

- The dominant sources of data for both TEFP and the current study included:
  - Statistics Canada: Reports on energy supply-demand in Canada. This was used for calibrating fuel use for each of the years, 2011 to 2015, in the current study.

4 NEB - National Energy Board (2017). Canada’s Energy Future 2017 - Energy Supply and Demand to 2040.

- Department of Natural Resources; Office of Energy Efficiency. This information was used for detailed disaggregation of final energy consumption for each of the 70 end uses in the NATEM model.
- Environment and Climate Change Canada: Annual National Inventory Reports. This information was used for calibrating GHG emissions coefficients.

- In addition to these sources of information, there are other reputable sources of data. These include, as examples, International Energy Agency (IEA), including technology briefs from IEA-ETSAP, U.S. Department of Energy, including Energy Information Administration and National Renewable Energy Laboratory, Canadian electrical utility organizations and provincial government departments.

- Information was also obtained from other stakeholder organizations and corporations, especially for information on emerging technologies, such as, developments in battery technology, solar PV installations, waste management, industrial process changes, and carbon capture, use and storage (CCUS).

- An important source of data was for nuclear generation. It was assumed that the nuclear refurbishment program for Ontario, as defined at the start of this study (July, 2018), would remain, as part of the committed program for electricity supply. Additional nuclear was included as a generation option for deriving minimum cost electricity supply for Ontario. The capital cost of new nuclear (Candu) was assessed at $6,955/kW ($2011). Interest during construction was assessed at 25% of capital cost, resulting in corresponding on-line cost of $8,693/kW. It was assumed that there would not be any additional cost for Ontario for processing nuclear waste from additional nuclear generation in the province. Decommissioning costs were excluded, which was consistent with all options for electricity supply and delivery.

Table 2. Macroeconomic drivers

Driver	Unit	2015	2020	2025	2030	2035	2040	2050
Socio-economic drivers								
Canada GDP	B $CAD 2011	1,912	2,110	2,287	2,479	2,710	2,931	3,425
Ontario GDP	B $CAD 2011	718	812	876	948	1,045	1,136	1,345
Canada Population	Millions	35,849	37,805	39,528	41,082	42,394	43,524	45,737
Ontario Population	Millions	13,797	14,691	15,338	15,908	16,452	16,822	17,481
International oil and gas prices								
Brent	$US 2016/bbl	$53	$69	$79	$80	$80	$80	$80
West Texas Intermediate	$US 2016/bbl	$49	$67	$77	$78	$78	$78	$78
Western Canadian Select	$US 2016/bbl	$36	$44	$53	$56	$59	$59	$59
Henry Hub - US$/MMBtu	$US 2016/MMBTU	$2.66	$3.35	$3.88	$4.03	$4.18	$4.33	$4.55

6 Results and Observations

This section of the study includes presentations and analyses of results of the three scenarios.

As noted above, primary attention will be given to comparing results of the second (FED) and third (FED+ON) scenarios with results of the first scenario (Reference scenario (REF)), for assessing changes, impacts and costs that are required for meeting the prescribed GHG mitigation targets. This begins with an overview, followed by assessments for the respective sectors.

6.1 Overview of results for GHG mitigation

Summary results for the three scenarios are shown on Table 1 and in Figures 7 to 12, inclusive. All emissions data presented in Figures 7 to 12 is for combustion emissions only. Key observations from a detailed review of background documentation and results are as follows:

- An initial, and important, observation is that it is possible to achieve an 80% reduction in combustion emissions by 2050 for Canada, and for each of its 13 jurisdictions, collectively, with currently proven and known emerging technologies. This represents a significant advance since completing the TEFP, where there were residual concerns about achieving this goal.

  Despite this, it still needs to be fully appreciated that achieving the 80% reduction goal in 2050 will be a formidable challenge.

- For the REF scenario (Figure 7), combustion emissions continue to increase in response to expanding energy-based demands, due to increasing population and a growing economy. For Canada as a whole, GHG emissions increase by 22% by 2050, relative to 2015. For Ontario, the growth is even greater, with associated GHG emissions increasing by 44%.

  It is noteworthy that the rate of growth of emissions is well below the rate of growth of the national GDP. This reflects the fact that it is cost efficient to implement energy conservation and energy efficiency programs even without considering GHG mitigation.

- For the other two scenarios, the model has to meet the same growing energy-based demands as for the REF scenario, but also to reduce emissions to meet the defined targets. The reductions reflect not only reductions from current GHG emissions, but also the need to offset increasing emissions that would normally occur in an expanding economy. This is a special challenge for Ontario as GHG emissions are projected to increase at a rate well above the national average, as shown on Figure 7. This is due primarily to higher growth rates in the industrial sector, a sector particularly important in Ontario.

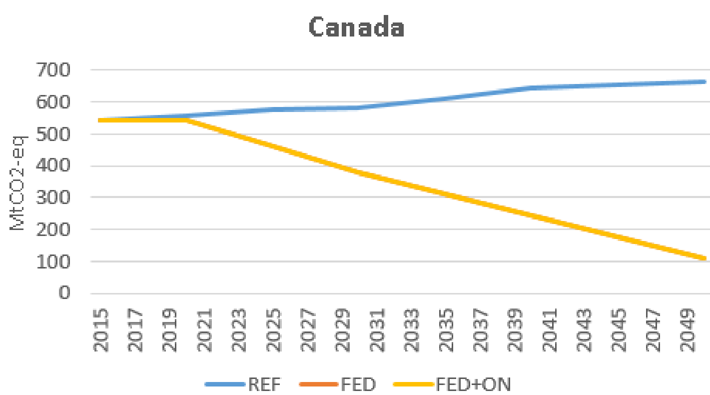
- Results, as shown on Figures 8 to 11, inclusive, indicate priority areas for achieving GHG mitigation at minimum present worth cost for all of Canada, and for Ontario.

  - The immediate priority is to completely decarbonize electricity supply, with Canada's entire electricity supply system being fully decarbonized before 2030. While this result is most dramatic in jurisdictions with thermal-dominated generating systems (Alberta, Saskatchewan, Nova Scotia), it also applies to Ontario.

  - Immediately following this, the transportation sector is the dominant sector for reducing combustion emissions. The primary strategy is electrification, especially for light duty vehicles and urban public transportation systems. There have also been encouraging developments with battery technology for heavy truck freight transport. Biofuels also become increasingly important (as noted below), especially for heavy freight transport.

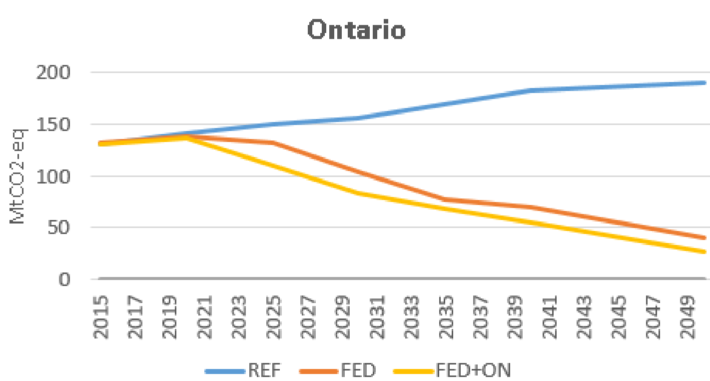
- Progressive reductions must also occur in the other sectors. The largest emitting sectors in Ontario, transportation and industrial, produce the greatest reductions in emissions to 2050; however, by 2050 they still remain as the largest sectors for producing GHG emissions. By 2050 the residential and commercial sectors are fully decarbonized.
- From comparing results of the FED and FED+ON scenarios for Canada (Figures 8 and 10, respectively), there are no substantive differences in overall trends.
- When comparing corresponding results for Ontario (Figures 9 and 11, respectively), the trends, again are consistent. The key observation is that transformations for the FED+ON scenario occur slightly earlier than for the FED scenario, reflecting the impacts of more stringent GHG mitigation requirements for the FED+ON scenario. As one example, the transport sector in Ontario produces only 3 Mt of combustion emissions in 2050 for the FED+ON scenario, as compared to 11 Mt for the FED scenario.

Figure 7. GHG trajectories



Canada	GHG growth (2015-2050)
REF (2)	+ 22%
FED (1)	- 80%
FED+ON (1)	- 80%

(1) Model input
(2) Model output



Ontario	GHG growth (2015-2050)
REF (2)	+ 44%
FED (2)	- 70%
FED+ON (1)	- 80%

(1) Model input
(2) Model output

Figure 8. GHG reductions by sector for Canada – FED scenario

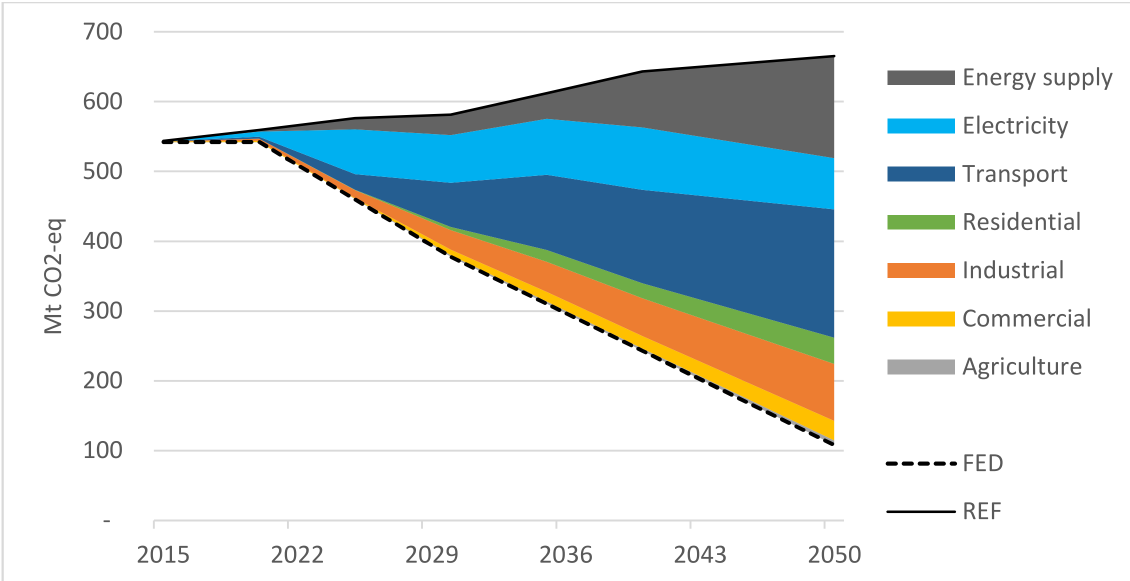


Figure 9. GHG reductions by sector for Ontario – FED scenario

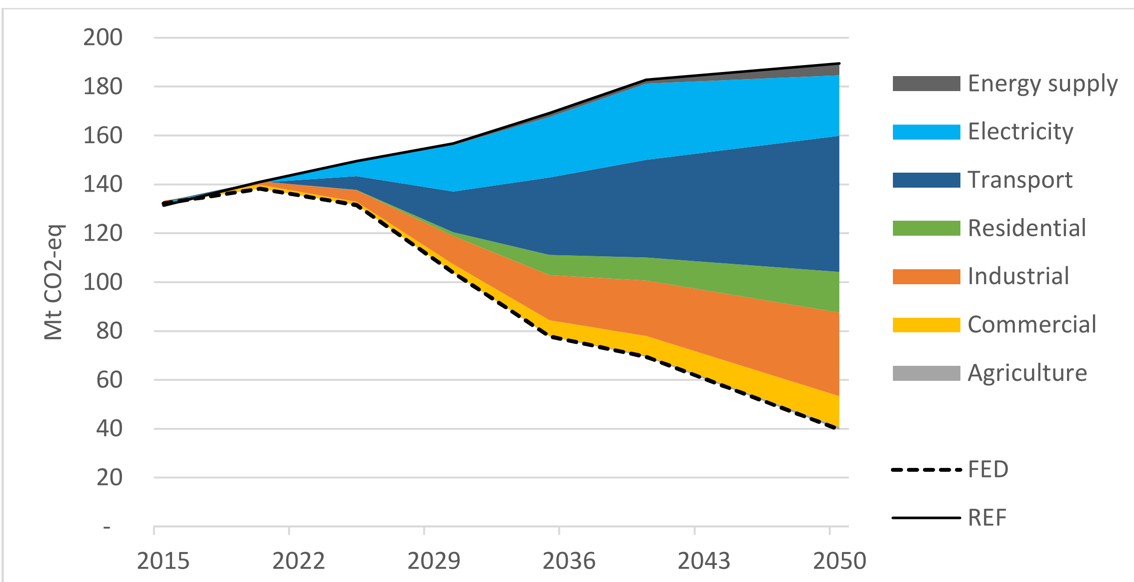


Figure 10. GHG reductions by sector for Canada – FED+ON scenario

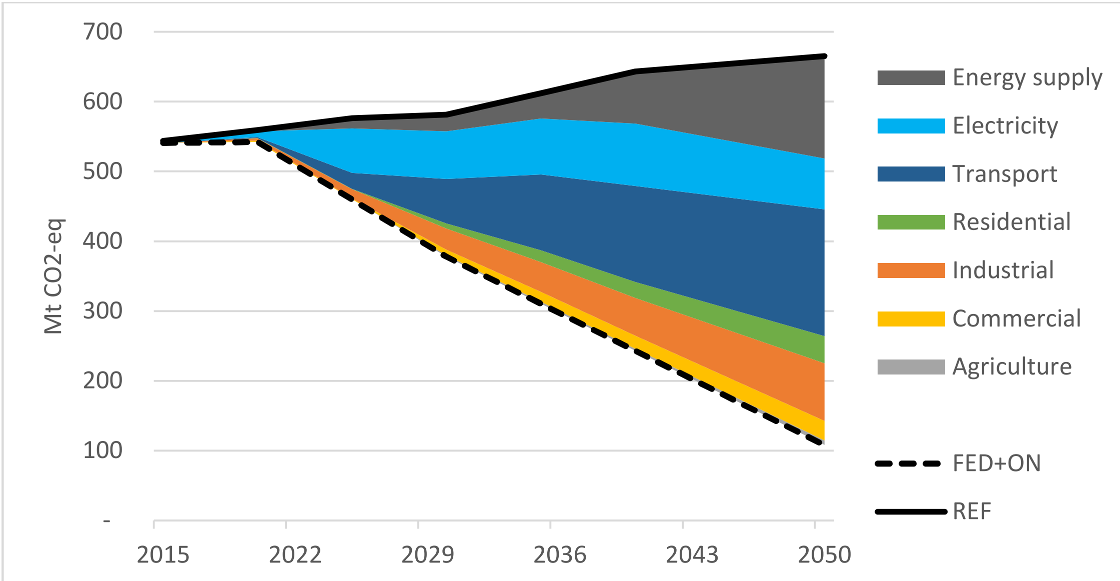


Figure 11. GHG reductions by sector for Ontario – FED+ON scenario

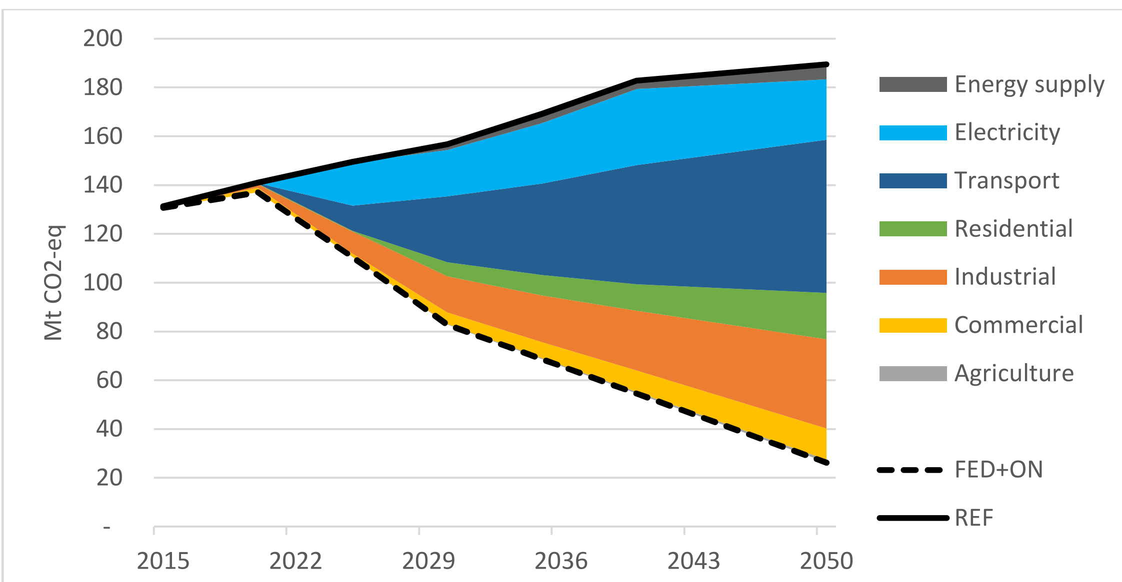
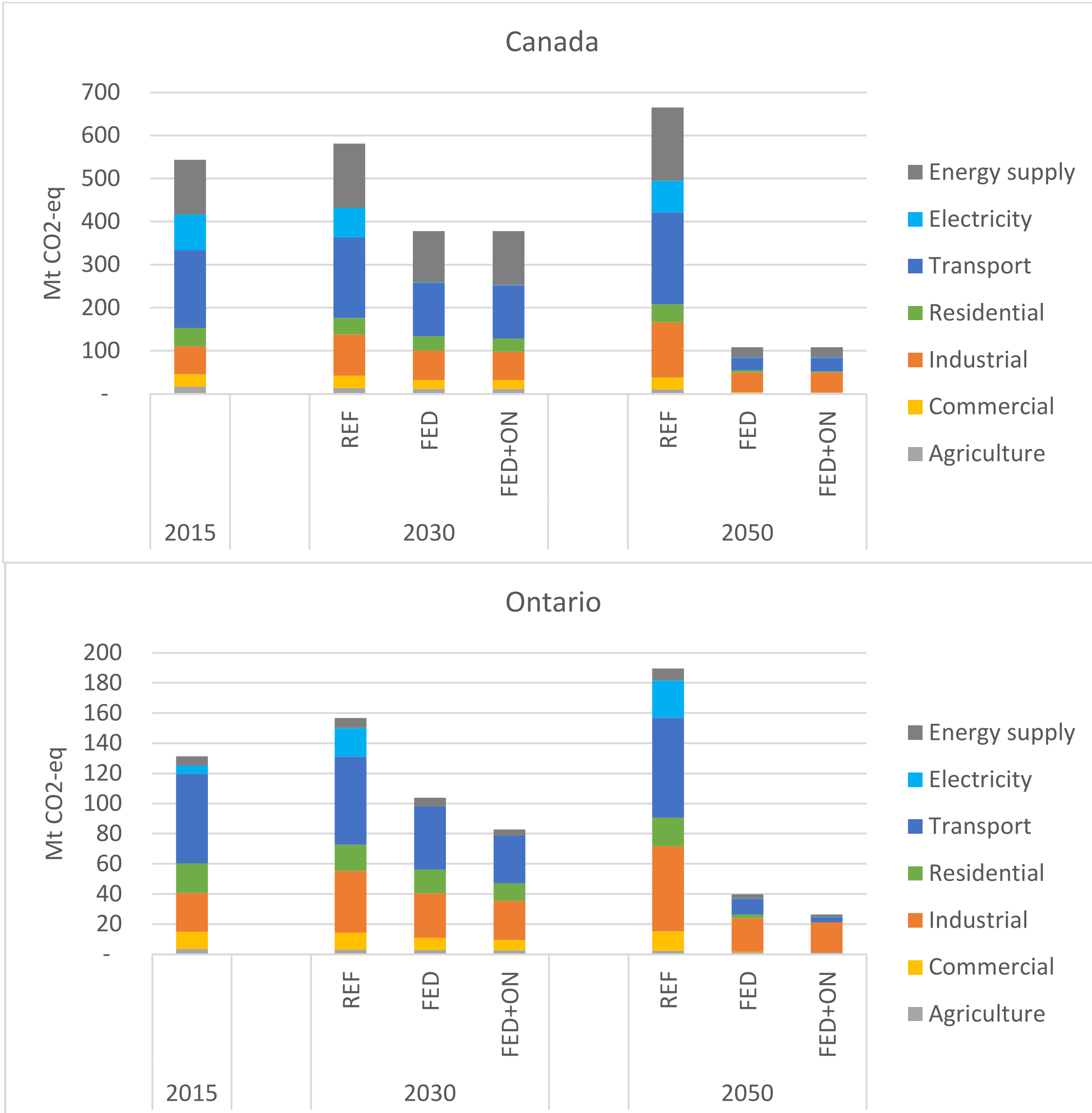


Figure 12. GHG emissions by sector



6.2 Final energy consumption

Summary results for final energy consumption for the three scenarios are shown on Figure 13. Key observations from a detailed review of the background documentation and results are as follows:

- For the REF scenario, there is a continuing increase in energy consumption, with the overall increase for all of Canada being 33%, from 7,768 petajoules (PJ) in 2015 to 10,302 PJ in 2050. The corresponding increase for Ontario is 37%, from 2,556 PJ to 3,498 PJ.

  With respect to the overall mix for final energy consumption, there are nominal shifts in percentages of the various sources. For Canada, use of fossil fuels increases from 5,398 PJ (69%) in 2015 to 6,961 PJ (68%) in 2050. Bioenergy declines, from 604 PJ (8%) to 583 PJ (6%), and electricity increases, from 1,750 PJ (23%) to 2,682 PJ (26%).

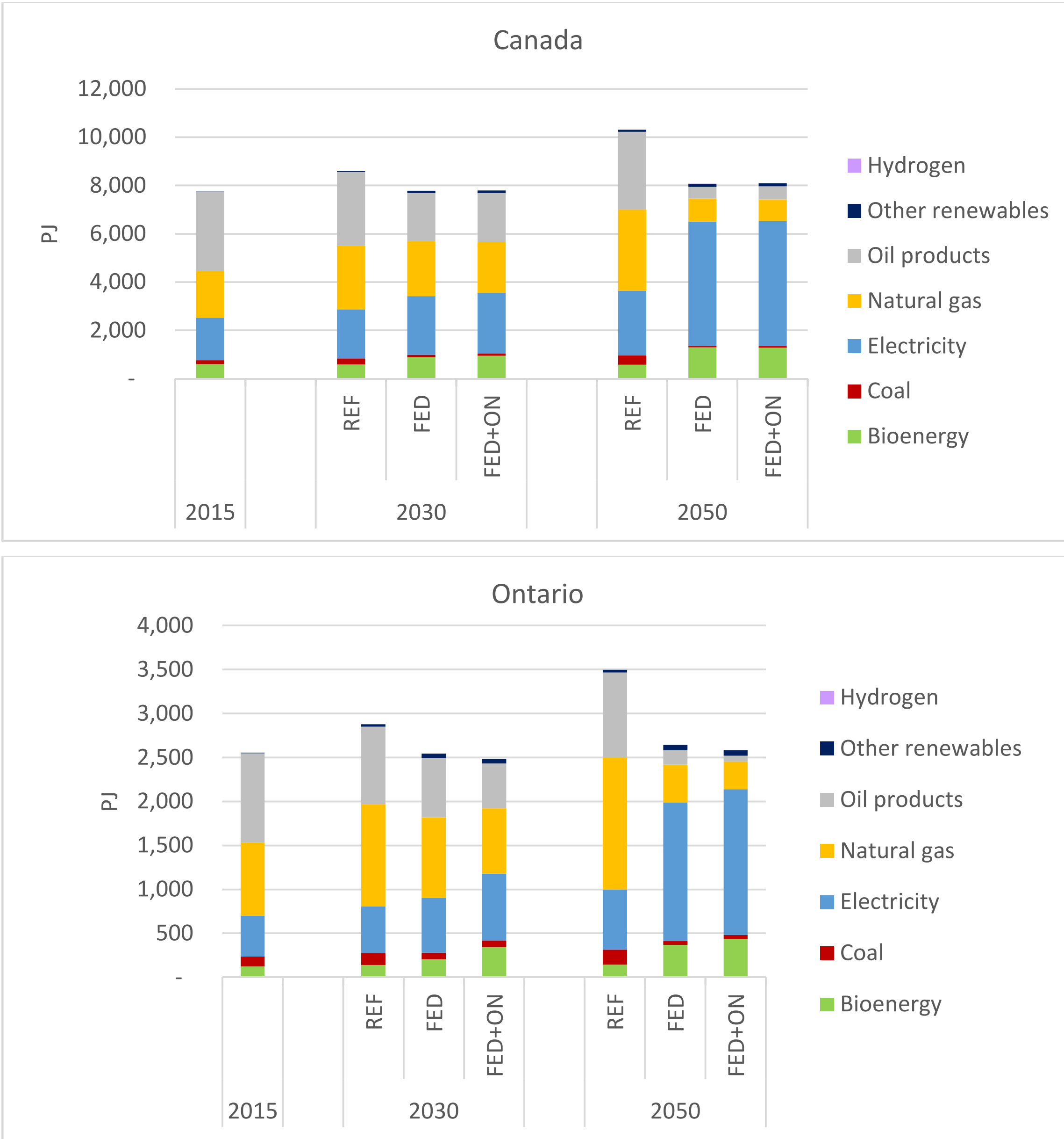
For Ontario, general trends are similar. Use of fossil fuels increases from 1,962 PJ (77%) to 2,637 PJ (75%). Bioenergy increases from 124 PJ (5%) to 145 PJ (4%). Electricity increases from 462 PJ (18%) to 685 PJ (20%)

- With respect to results of the two mitigation scenarios (FED and FED+ON), there are several major differences from the results of the REF scenario.
  - For both scenarios, final energy consumption remains essentially constant for the entire period to 2050. For all of Canada, the increase for both scenarios, from 2015 to 2050, is 1%. For Ontario, the increases are 3% for the FED scenario and 1% for the FED+ON scenario. Additional energy efficiency options, including fuel substitution away from the use of fossil fuels, result in substantial reductions in energy consumption, relative to the REF scenario.
  - There are, however, major changes in the energy supply mix. For Canada, the role of electricity increases from 23% for 2015, to 31% (32% for FED+ON scenario) in 2030, and to 64% for both scenarios in 2050 (approximately three-fold increase). The role of bioenergy increases from 8% in 2015 to 16% in 2050. Use of fossil fuels declines correspondingly, from 70% in 2015 to 56% in 2030 (55% for FED+ON scenario) to 19% (18% for FED+ON scenario) in 2050.

    There are corresponding major changes in the supply mix for Ontario. For the FED scenario, the role of electricity increases from 18% in 2015 to 25% in 2030 and to 60% in 2050. The role of biofuels increases from 5% in 2015 to 8% in 2030 and to 14% in 2050. The role of fossil fuels decreases correspondingly from 77% in 2015 to 65% in 2030 and to 24% in 2050. The role of other forms of renewable energy (dominantly, passive solar and ambient geothermal for heat pumps) also increases, from 0.3% in 2015 to 2% in 2030 and to 2.3% in 2050.
  - There are further impacts on the supply mix for Ontario for the FED+ON scenario, relative to the results for the FED scenario, as reported above. Because of the more stringent GHG mitigation targets in the FED+ON scenario, the role of fossil fuels in 2050 declines from 24% in the FED scenario to 17% in the FED+ON scenario. This is achieved with the role of electricity increasing from 60% in the FED scenario to 64% in the FED+ON scenario, and with bioenergy increasing from 14% in the FED scenario to 17% in the FED+ON scenario.
  - For the two GHG mitigation scenarios, there are major reductions in the use of all fossil fuels, including coal, natural gas and oil. The largest reduction, however, is with use of oil and oil products. For all of Canada, the reduction is from 3,296 PJ in 2015 to 486 PJ (85% reduction) in 2050 for the FED scenario. The role of oil for meeting Canada's reliance on total energy needs reduces correspondingly from 42% in 2015, to only 6% in 2050 for the FED scenario. Results for the FED+ON scenario are closely comparable.

    For Ontario, the trends are similar. Use of oil and oil products reduces from 1,017 PJ in 2015 to 162 PJ in 2050 (84% reduction) in 2050 for the FED scenario, or to 68 PJ (93% reduction) for the FED+ON scenario. The role of oil and oil products for meeting Ontario's energy needs would reduce correspondingly from 40% in 2015, to 6% in 2050 for the FED scenario, or even as low as 3% for the FED+ON scenario.

Figure 13. Final energy consumption



6.3 Electricity sector

Summary results for electricity demand and corresponding production (energy and capacity, respectively) for the three scenarios are shown on Figures 14 to 16, inclusive, and on Table 3. Key observations from a detailed review of the background documentation and results are as follows:

- As noted above, for the REF scenario, electricity consumption, for all of Canada, increases from 1750 PJ (486 TWh) in 2015 to 2,682 PJ (745 TWh) in 2050. Electricity generation, which includes meeting electricity consumption, export, auto-consumption, and system losses, increases from 645 TWh in 2015 to 957 TWh in 2050.

For Ontario, electricity consumption increases from 462 PJ (128 TWh) in 2015 to 685 PJ (190 TWh) in 2050. For the REF scenario, electricity generation increases from 159 GWh in 2015 to 245 GWh in 2050.

- There are nominal changes in the supply mix for electricity generation for all of Canada in the REF scenario. Thermal generation, dominantly gas-fired generation, increases from 125 TWh (19% of total generation) in 2015 to 243 TWh (25%) in 2050. Hydro increases from 393 TWh (61%) in 2015, to 540 TWh (56%) in 2050. Nuclear generation declines from 96 TWh (15%) in 2015, to 55 TWh (6%) in 2050. The other changes include wind, increasing from 27 TWh (4%) to 36 TWh (4%) in 2050, and solar, increasing from 3 TWh (0.5%) in 2015, to 82 TWh (8.6%) in 2050.

  There are several significant projected changes in the electricity supply mix for Ontario in the REF scenario. The largest change is with gas fired thermal generation, increasing from 13 TWh (8%) in 2015 to 83 TWh (34%) in 2050. Nuclear generation declines from 96 TWh (61%) in 2015, to 55 TWh (22%) in 2050. Hydro remains unchanged at 37 TWh (23% in 2015 reducing to 15% in 2050). Wind generation increases from 10 TWh (6%) in 2015 to 18 TWh (7%) in 2050, while solar increases from 3 TWh (1.9%) in 2015, to 52 TWh (21%) in 2050.

- As noted in Section 6.2, there are enormous increases in electricity consumption with the two mitigation scenarios, with associated increases in electricity generation. For the FED scenario, electricity generation for all of Canada increases from 645 TWh in 2015, to 882 TWh in 2030 (37% increase), and to 2,005 TWh (3.1-fold increase) in 2050. Results for the FED+ON scenario are comparable. For Ontario, growth in electricity demand also increases approximately 3-fold. However, this is not reflected in comparable growth in electricity generation in Ontario, as the minimum cost solution results in major electricity import from Quebec.

- These large increases in electricity demand result in major additions in electricity generating capacity. For all of Canada, total generating capacity for the FED scenario increases from 151 GW to 735 GW (almost five-fold increase). This includes a roughly three-fold increase in electrical energy demand and the further increase in dependable capacity associated with large increases in generation from intermittent renewables (wind and solar). Results for the FED+ON scenario are closely comparable.

- There are major changes to the electricity supply mix for Ontario.

  - There are significant investments in renewables generation, including hydro and intermittent renewables generation, including both wind and solar. Virtually all remaining hydro potential in Ontario is fully developed. Because of the large addition of intermittent renewables generation, there is also investment in pumped storage for grid scale dependable capacity. As already noted, the minimum cost solution also results in major electricity imports from Quebec, with associated investments in high voltage interconnections.

  - Even with the relatively high unit costs for nuclear generation used in this study (see Section 5.2), the overall minimum cost solution results in investment in additional nuclear for Ontario. This includes 2.93 GW of additional nuclear capacity in Ontario in 2050 for the FED scenario, and 10.03 GW in Ontario for the FED+ON scenario. The minimum cost solution also results in additional nuclear capacity in Alberta in 2050, at 1.9 GW for the FED scenario and 2.4 GW for the FED+ON scenario. There is no additional nuclear capacity selected in any other jurisdiction.

- With respect to the nuclear option in Ontario, there are additional perspectives which need to be considered:
    - Nuclear becomes an important long term option for generation supply as there is an upper limit on availability of hydro potential in Canada. Based on the minimum cost solution, virtually all remaining hydro potential in Quebec and Ontario will be fully developed by 2050. At that stage, nuclear becomes a more important option for both base load generation and dependable capacity.
    - This current study results in less nuclear generation than were derived in TEFP (2016). The principal reasons are that costs of intermittent renewables, especially solar, have declined more rapidly than assumed in the TEFP. An *incremental hydro* option has also been included in the current study, which is a source of relatively low cost dependable capacity, for complementing lack of dependable capacity contributions from wind and solar. The *incremental hydro* option refers to the addition of generating capacity at existing and future hydro sites.
    - In the TEFP, one of the scenarios was based on the premise of *no more nuclear* in Canada. The results showed that the generation supply mix changed dramatically, with major increases in intermittent renewables, grid scale pumped storage, and high voltage interconnections. The hydro program proceeded more rapidly, and energy exchange between jurisdictions increased. While the overall cost for the *no more nuclear* was higher, the differential cost, surprisingly, between the two scenarios, was very small.

It is important to appreciate that these results are based on information and data that needs to be updated and improved. For Ontario, these data could be revised using more recent information[5]. However, existing information on hydro potential for all of Canada is old and requires updating. Similarly, information on pumped storage potential is based on generic data, as there is no existing inventory of pumped storage potential, including costs, for Canada. Conceptual studies have been carried out for specific sites, but no comprehensive inventory exists for the whole country. These options merit much more precise information and detailed assessment when considering minimum cost pathways for Ontario's electricity sector.

5 Hatch Acres (2005). Evaluation and Assessment of Ontario's Waterpower Potential. Final Report prepared for Ontario Waterpower Association and Ontario Ministry of Natural Resources. 55 p.

Table 3. Electricity generation and installed capacity for Canada

Time period	2015	2030			Growth 2015-2030			2050			Growth 2015-2050		
Generation (Twh)	**REF**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**
Hydro	393	454	625	658	16%	59%	67%	540	782	782	37%	99%	99%
Fossil-fuelled	125	197	32	31	58%	-74%	-75%	243	68	58	94%	-46%	-54%
Nuclear	96	71	71	71	-26%	-26%	-26%	55	91	148	-43%	-5%	54%
Wind	27	40	138	132	48%	411%	389%	36	908	883	33%	3263%	3170%
Solar	3	3	6	6	0%	100%	100%	82	124	122	2633%	4033%	3967%
Biomass	1	1	10	9	0%	900%	800%	1	21	19	0%	2000%	1800%
Other Renewable	0	0	0	0	0	0	0	0	10	10	0	0	0
TOTAL	**645**	**766**	**882**	**907**	**19%**	**37%**	**41%**	**957**	**2,004**	**2,022**	**48%**	**211%**	**213%**

Time period	2015	2030			Growth 2015-2030			2050			Growth 2015-2050		
Capacity (GW)	**REF**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**
Hydro	83	93	128	135	12%	54%	63%	106	163	163	28%	96%	96%
Fossil-fuelled	36	35	27	26	-3%	-25%	-28%	38	87	75	6%	142%	108%
Nuclear	14	10	10	10	-29%	-29%	-29%	7	12	20	-50%	-14%	43%
Wind	11	17	47	46	55%	327%	318%	15	319	309	36%	2800%	2709%
Solar	2	3	5	5	50%	150%	150%	68	102	100	3300%	5000%	4900%
Biomass	4	4	5	5	0%	25%	25%	4	7	7	0%	75%	75%
Other Renewable	0	0	0	0	0	0	0	0	2	2	0	0	0
Storage	0	1	4	3	0	0	0	9	43	51	0	0	0
TOTAL	**150**	**163**	**226**	**230**	**9%**	**51%**	**53%**	**247**	**735**	**727**	**65%**	**390%**	**385%**

Table 4. Electricity generation and installed capacity for Ontario

Time period	2015	2030			Growth 2015-2030			2050			Growth 2015-2050		
Generation (Twh)	**REF**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**
Hydro	37	37	57	90	0%	54%	143%	37	93	93	0%	151%	151%
Fossil-fuelled	13	51	0	0	292%	-100%	-100%	83	9	0	538%	-31%	-100%
Nuclear	96	67	67	67	-30%	-30%	-30%	55	77	130	-43%	-20%	35%
Wind	10	19	19	19	90%	90%	90%	18	45	27	80%	350%	170%
Solar	3	3	3	3	0%	0%	0%	52	52	52	1633%	1633%	1633%
Biomass	0	0	1	1	0	0	0	0	3	0	0	0	0
Other Renewable	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	**159**	**177**	**147**	**180**	**11%**	**-8%**	**13%**	**245**	**279**	**302**	**54%**	**75%**	**90%**

Time period	2015	2030			Growth 2015-2030			2050			Growth 2015-2050		
Capacity (GW)	**REF**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**	**REF**	**FED**	**FED+ON**
Hydro	9	9	14	22	0%	56%	144%	9	22	22	0%	144%	144%
Fossil-fuelled	9	10	9	9	11%	0%	0%	12	16	6	33%	78%	-33%
Nuclear	13	9	9	9	-31%	-31%	-31%	7	10	17	-46%	-23%	31%
Wind	4	9	9	9	125%	125%	125%	8	19	12	100%	375%	200%
Solar	2	2	2	2	0%	0%	0%	29	42	42	1350%	2000%	2000%
Biomass	0	1	1	1	0	0	0	1	1	1	0	0	0
Other Renewable	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	0	0	0	0	0	0	0	4	19	26	0	0	0
TOTAL	**37**	**40**	**44**	**52**	**8%**	**19%**	**41%**	**70**	**129**	**126**	**89%**	**249%**	**241%**

Figure 14. Electricity consumption by sector for Canada and Ontario

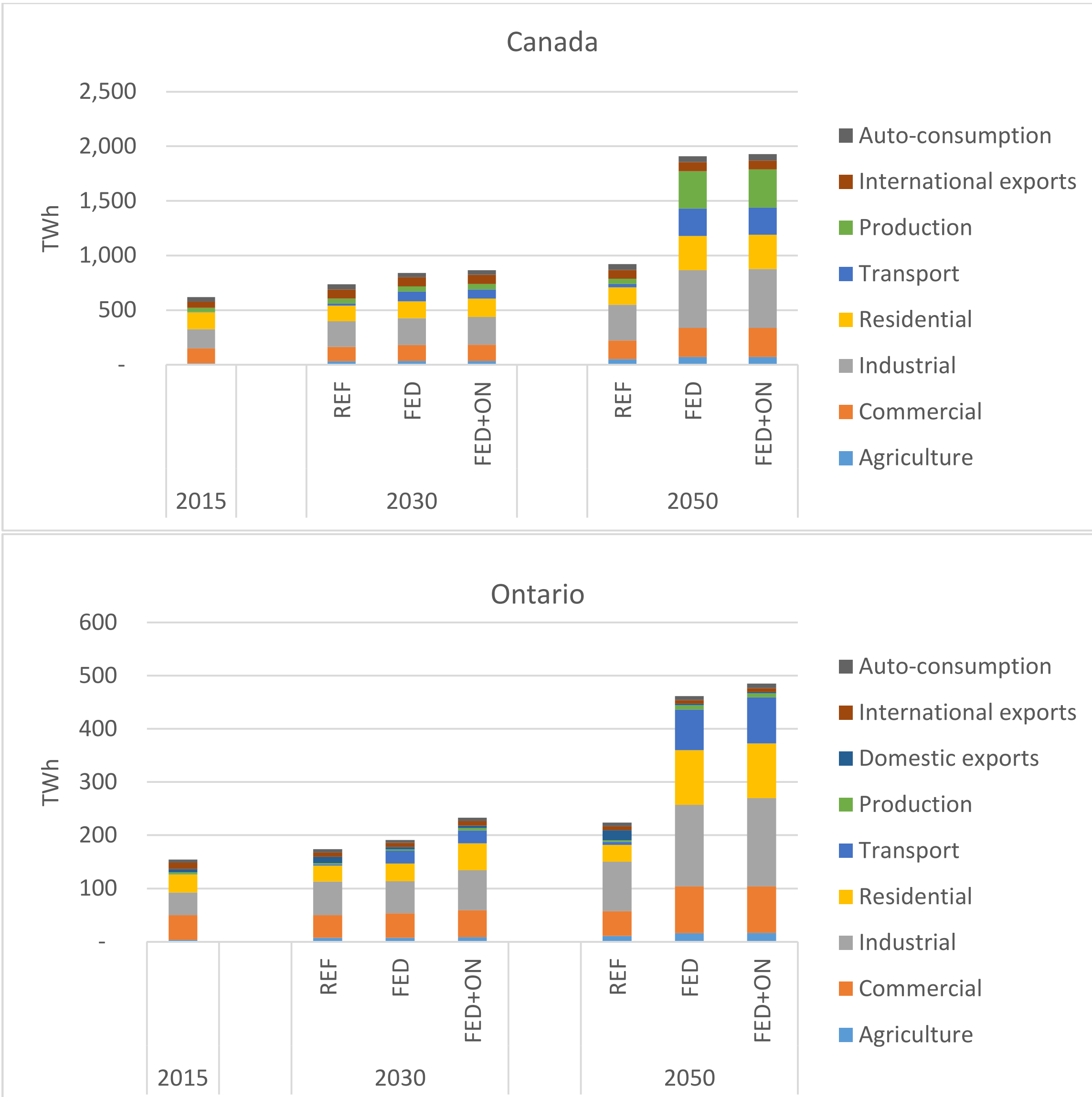
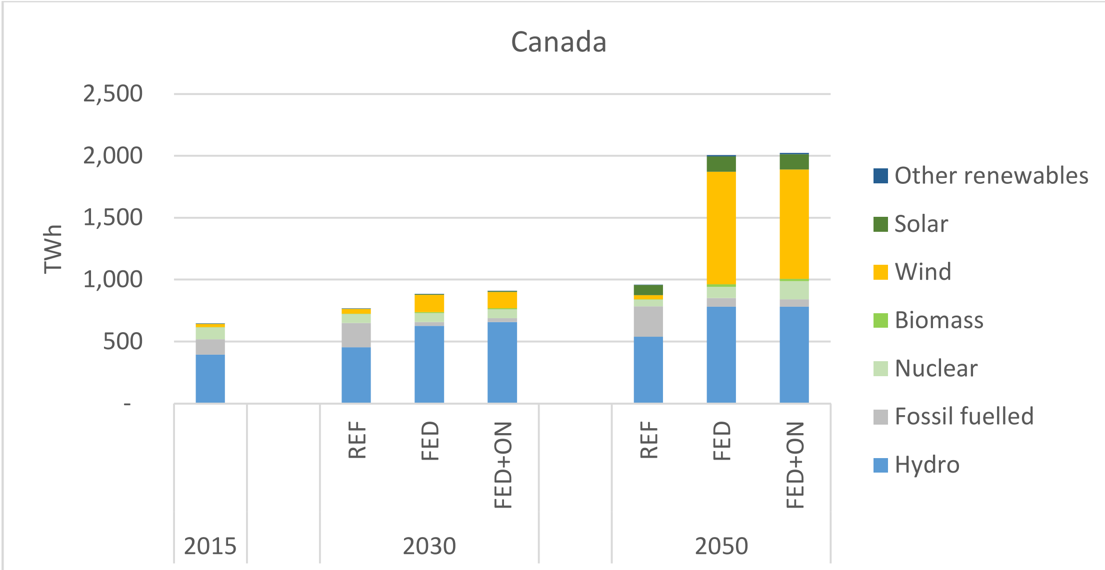


Figure 15. Electricity generation by type



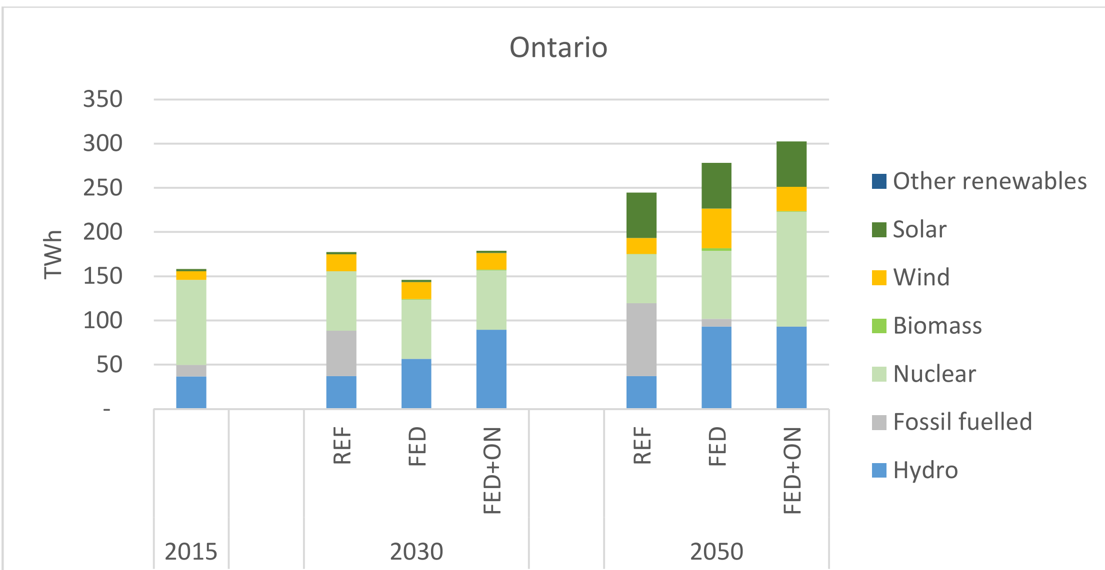
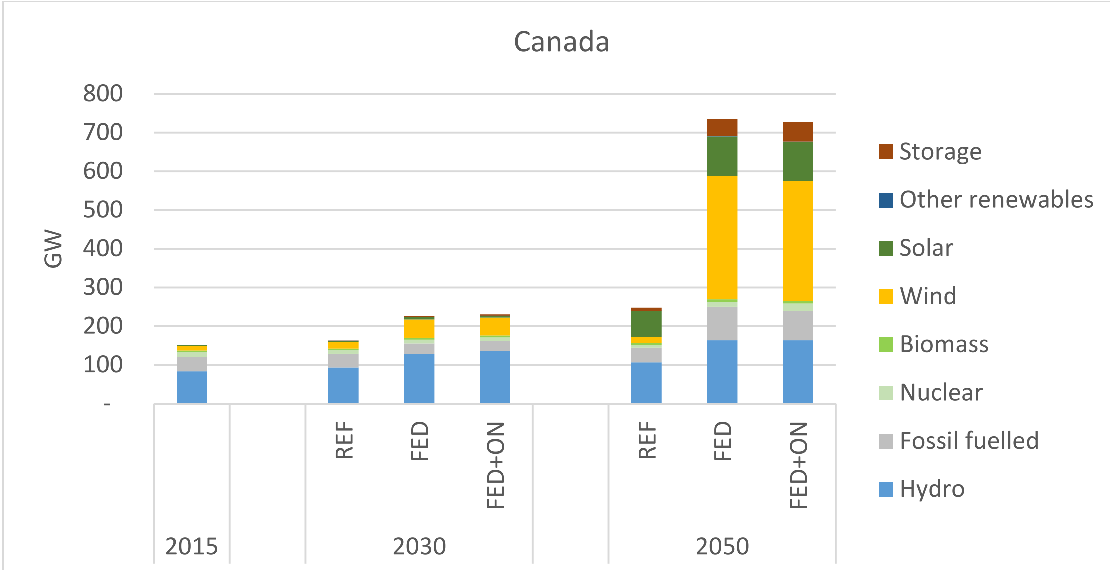
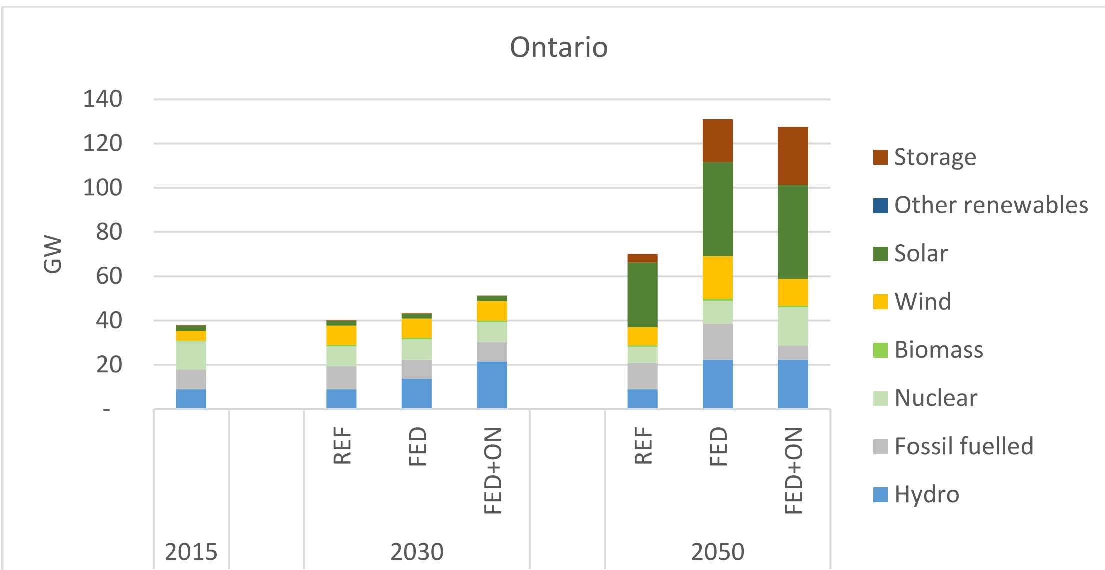


Figure 16. Electricity capacity by type





6.4 Bioenergy

Summary results for biomass and biofuels consumption and production are shown on Figures 17 & 18, respectively. Key observations from a detailed review of the background documentation and results are as follows:

- For the REF scenario, there is only a modest increase in demand for bioenergy. The main shift is with methanol replacing ethanol as a biofuel. The use of biomass for electricity and heat production remains essentially unchanged.
- For the two mitigation scenarios, there are major increases (roughly three-fold) in the use of bioenergy. The main changes include the production of renewable natural gas (biomethane and synthetic gas (syngas)) to replace fossil based natural gas, and the production of second

generation biofuels, including cellulosic ethanol and synthetic diesel from biomass gasification.

- Production of biofuels comes from several different sources, as shown in Figure 18. While some of these sources are from dedicated crops (corn, wheat, and canola production), it is of special note that much of the potential for the production of bioenergy is from other sources, including municipal waste and residues from the industrial, agriculture and forestry sectors.

Figure 17. Bioenergy consumption by type

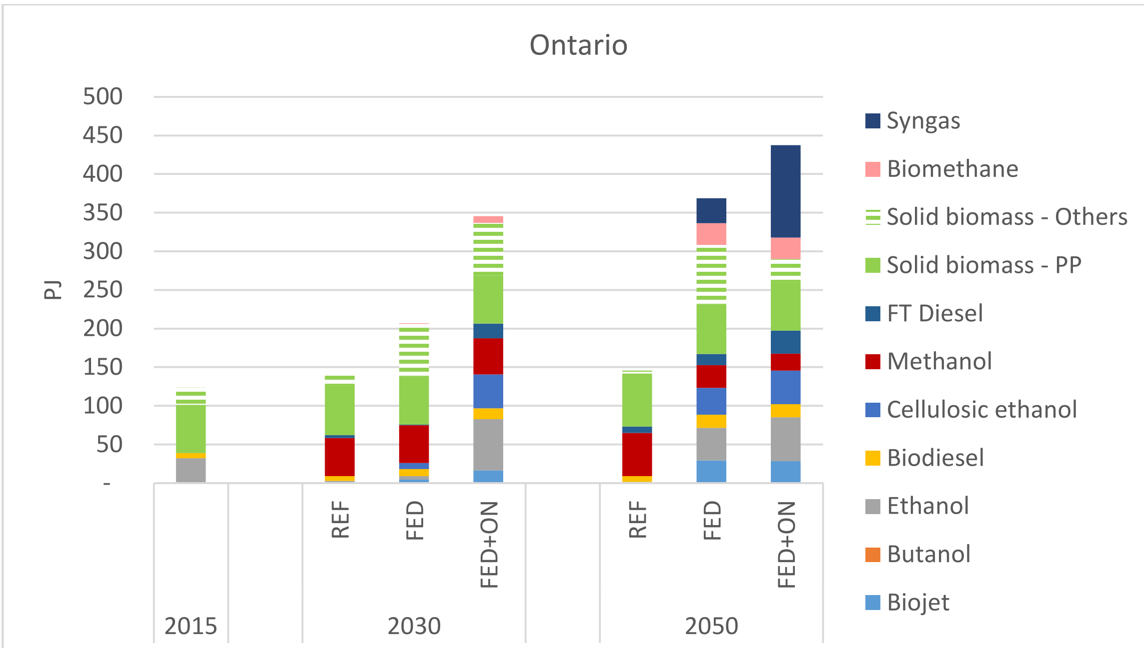
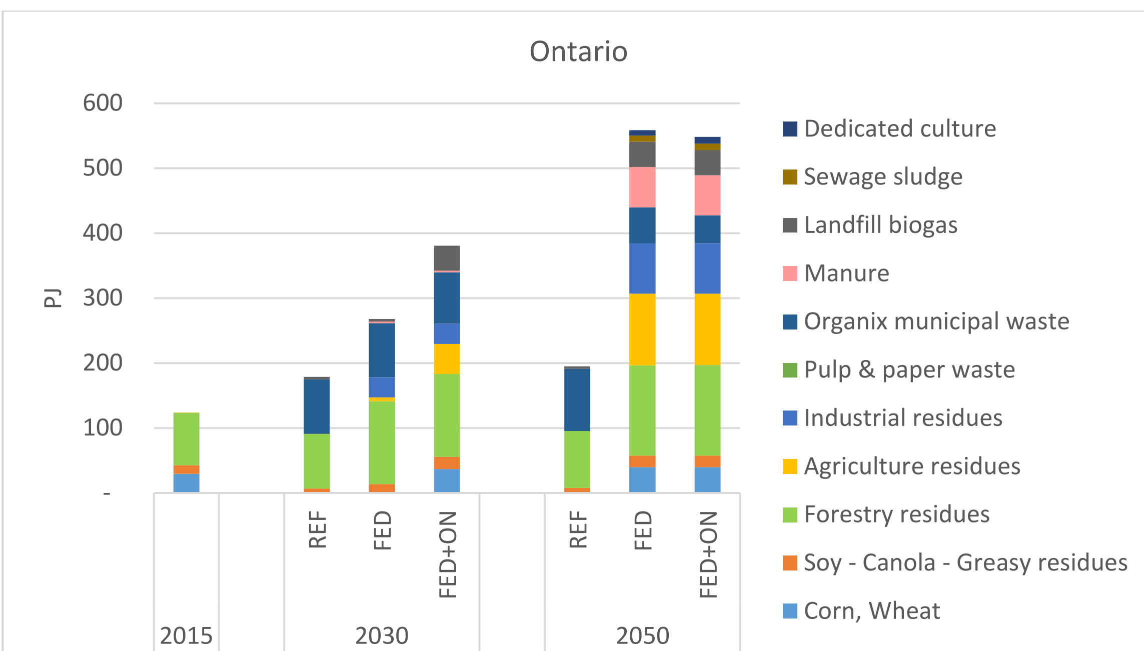


Figure 18. Biomass sources by type



6.5 Transportation sector

Summary results for GHG emissions from the transportation sector for the three scenarios are shown on Figures 19 to 24, inclusive. Key observations from a detailed review of the background documentation and results are as follows:

- As shown in Figures 1 to 4, the transportation sector is the largest sector for the production of GHG emissions. For 2016 (Figure 1), the transportation sector produced 27% of Canada's total GHG emissions, or 37% of Canada's total combustion emissions. Emissions from the transportation sector in Ontario are even more prominent, with the sector in 2016 producing 37% of total GHG emissions, equivalent to 50% of total combustion emissions (Figure 2).
- As shown in Figure 19, emissions from this sector are dominantly from cars and light duty vehicles and from freight trucks. The remaining emissions are from buses, trains, airplanes, marine transport and off-road transport.
- For the REF scenario, energy demand for the transportation sector for all of Canada increases from 2,815 PJ in 2015, to 3,011 PJ in 2030, and to 3,466 PJ in 2050. However, energy demand for passenger transport declines as a result of effects of the CAFE standards (Figure 20), while energy demand for freight transport continues to increase (Figure 23).

  Similarly, for Ontario, energy demand for the transportation sector increases from 924 PJ in 2015 to 946 PJ in 2030, and to 1075 PJ in 2050.

  The associated change in the mix of combustion emissions for the transportation sector, for both Canada and Ontario, are shown on Figure 19.

  It is noted that the solution mix includes natural gas/LNG as part of the minimum cost solution, for freight and marine transport, for an interim period only. The principal reason for becoming part of the solution mix in 2030 is that GHG emissions for a unit of energy for natural gas are about 30% lower than for diesel fuel. However, by 2050, diesel fuel and natural gas/ LNG are both progressively replaced by electricity and biofuels for satisfying more stringent GHG mitigation requirements.

  It is of special note that the energy system representation for this study did not include fugitive emissions associated with the whole natural gas supply chain. This may be an important consideration, which would tend to result in a solution mix with less, and possibly no, natural gas/ LNG for heavy freight and marine transport. It is especially important that this aspect be studied in detail.
- As noted in Section 6.1, major reductions for the mitigation scenarios occur early for the transportation sector. For all of Canada, for the FED scenario, emissions decline from 181 Mt in 2015, to 124 Mt in 2030, and to 29 Mt in 2050. Results for the FED+ON scenario are very similar.

  For Ontario, the corresponding reductions, for the FED scenario, are from 60 Mt in 2015 to 42 Mt in 2030 and to 11 Mt in 2050. For the FED+ON scenario, reductions are even greater, to 32 Mt in 2030 and 3 Mt in 2050.
- The large reductions in emissions in the transportation sector for the mitigation scenarios are achieved primarily with the electrification for road and urban transportation systems, energy efficiency improvements, and use of biofuels.

One of the advantages with using electric vehicles is that the energy conversion efficiency with electric motors is very high (normally more than 90%), while the energy conversion efficiency of internal combustion engines (ICE) is normally less than 30% (due to thermodynamic limitations). As a result, primary energy supply will decrease with the conversion to electric transport.

- The potential transition for light duty vehicles (cars and passenger trucks) for Ontario is shown on Figure 22. For the REF scenario, the dominant mode of transport is with ICE vehicles to 2050, but with nominal penetration of electric, hybrid and plug-in hybrid vehicles.

  For the mitigation scenarios, however, the transition is dramatic. There is a rapid penetration of electric and hybrid vehicles, with ICE vehicles being, in essence, fully replaced by 2050.

- There are additional important perspectives for reducing emissions in the transportation sector in the most cost effective manner.
  - This study was carried out with only two mitigation scenarios, and without time to carry out sensitivity analyses on important parameters. It is known, for example, that unit costs for electric transport for light duty vehicles and for freight transport may be closely competing, which may result in modified combinations of derived solutions for minimum cost mitigation for the transportation sector. It will also be important for the generic data used in this study to be confirmed or modified to more accurately reflect conditions in Ontario.
  - It is important that options which may not have been adequately explored in this study not be eliminated from further consideration. For example, there is considerable current research and development activity on the role of hydrogen for the transportation sector. This requires more updated representation in future runs of the model.
  - An important aspect from TEFP was the demonstration of overall cost reductions in the transportation sector with improved urban planning, especially for major urban regions. This included the importance of urban densification, multi-modal transportation planning, village clusters, public transportation, and emphasis on walking and cycling. The overall effect was a significant reduction in energy use and associated emissions for the transportation sector.

Figure 19. GHG emissions by transportation mode

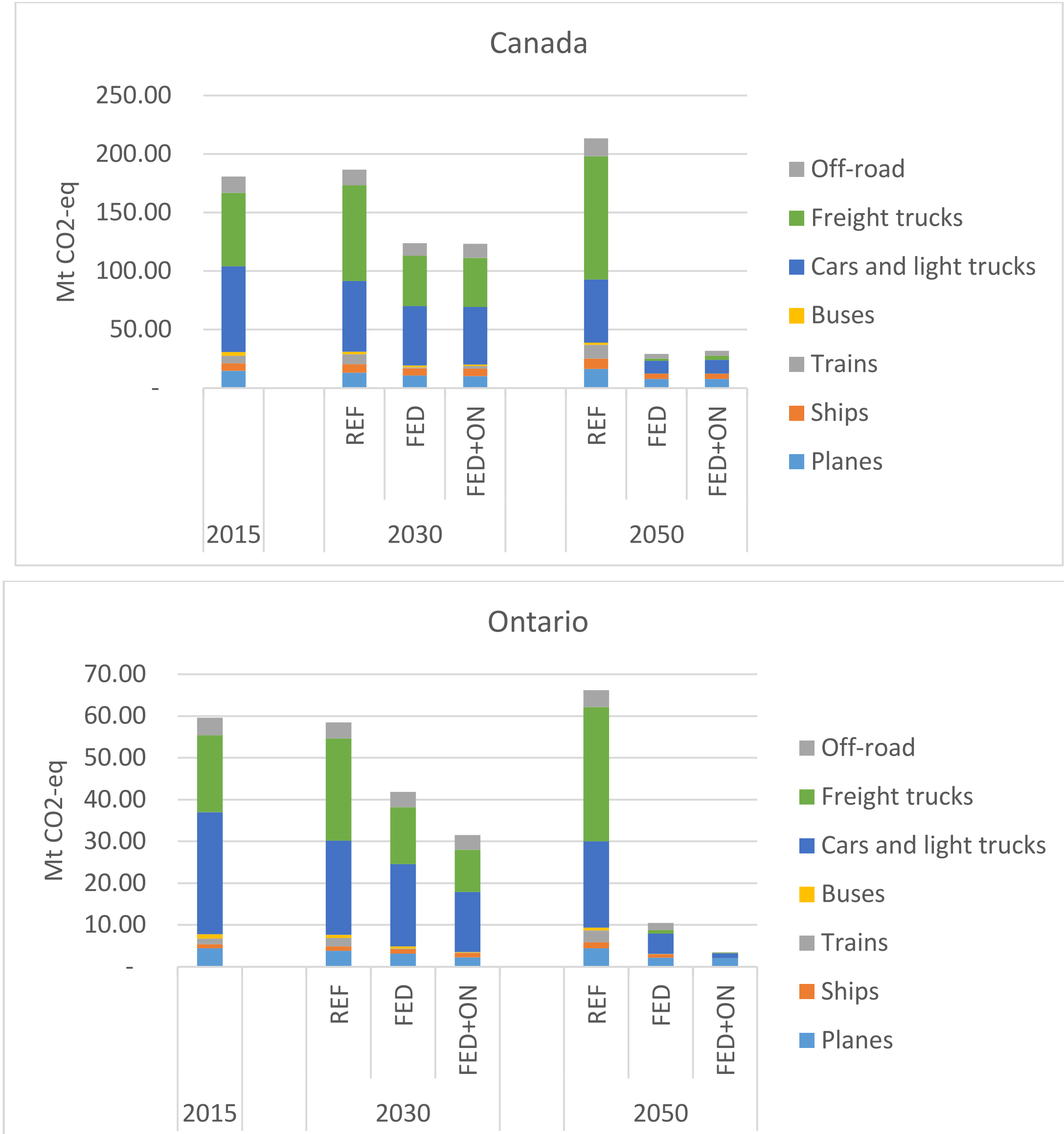
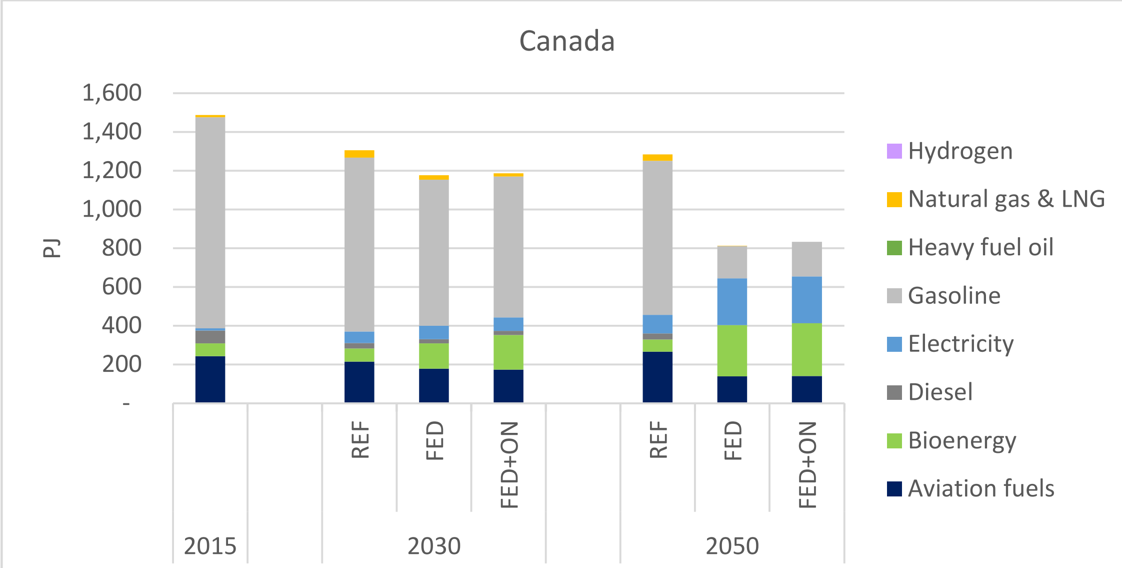


Figure 20. Final energy consumption by fuel– Passenger transport



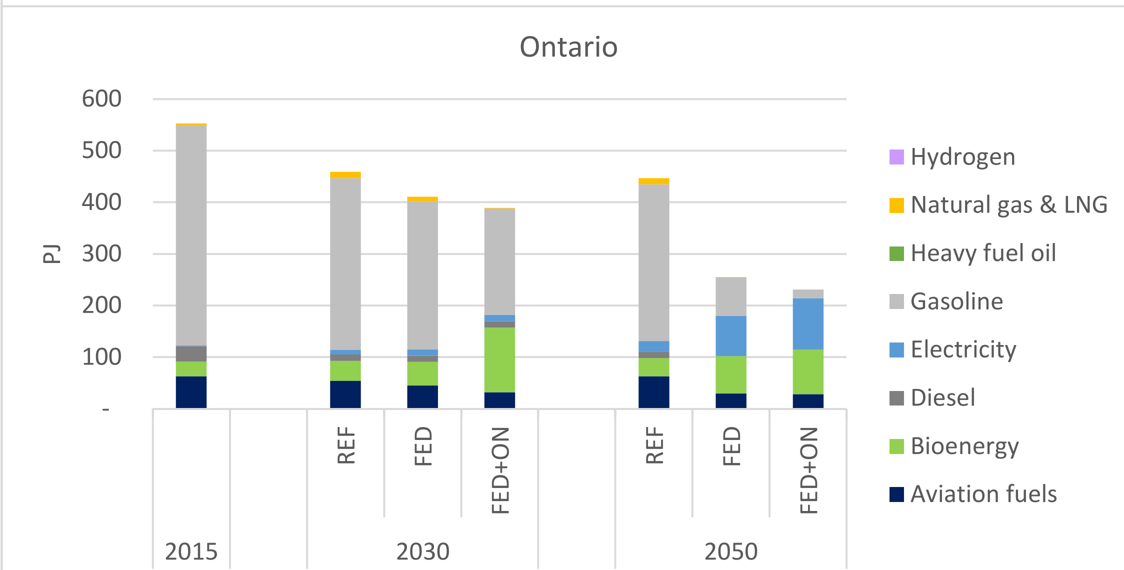
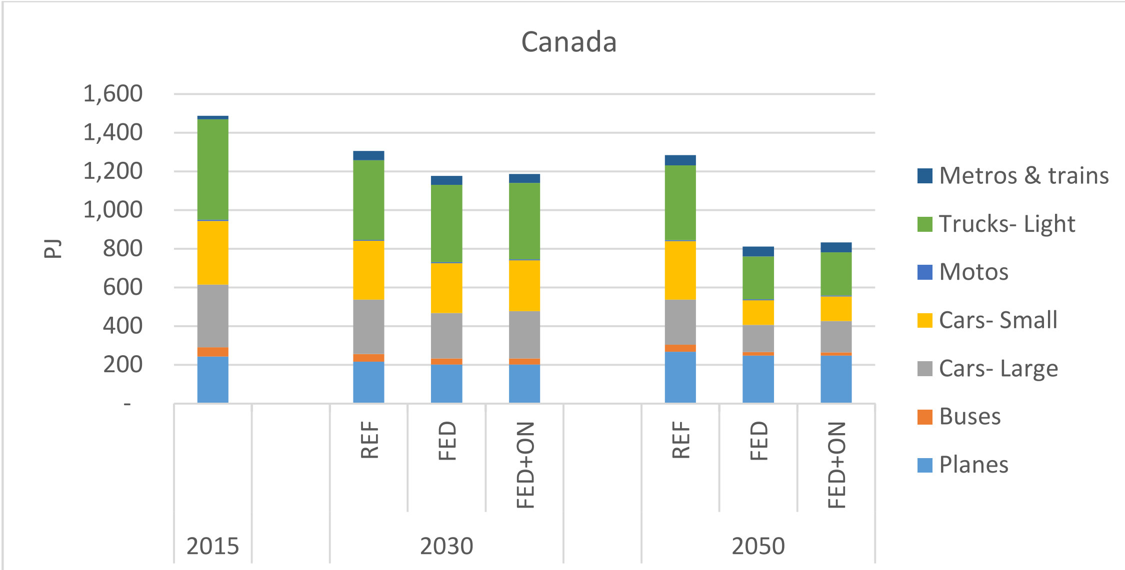


Figure 21. Final energy consumption by mode – Passenger transport



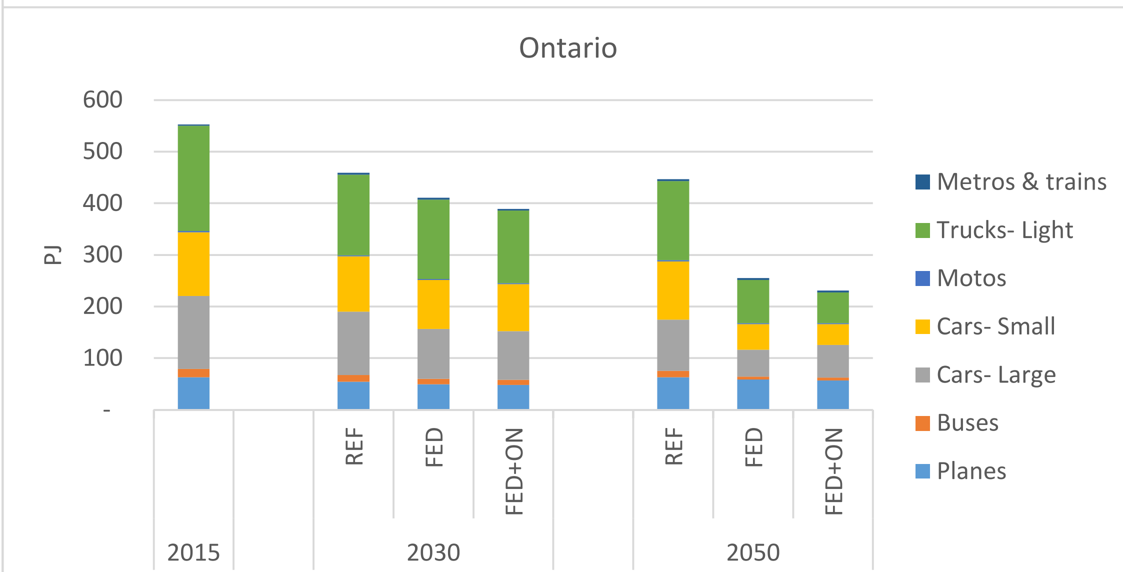


Figure 22. Market shares for light duty vehicles

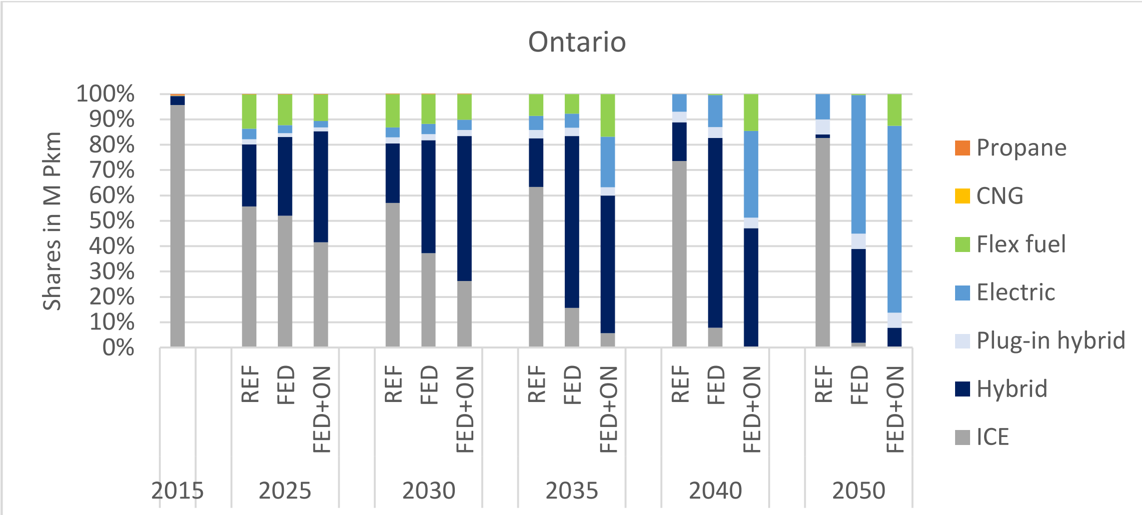


Figure 23. Final energy consumption by fuel – Freight transport

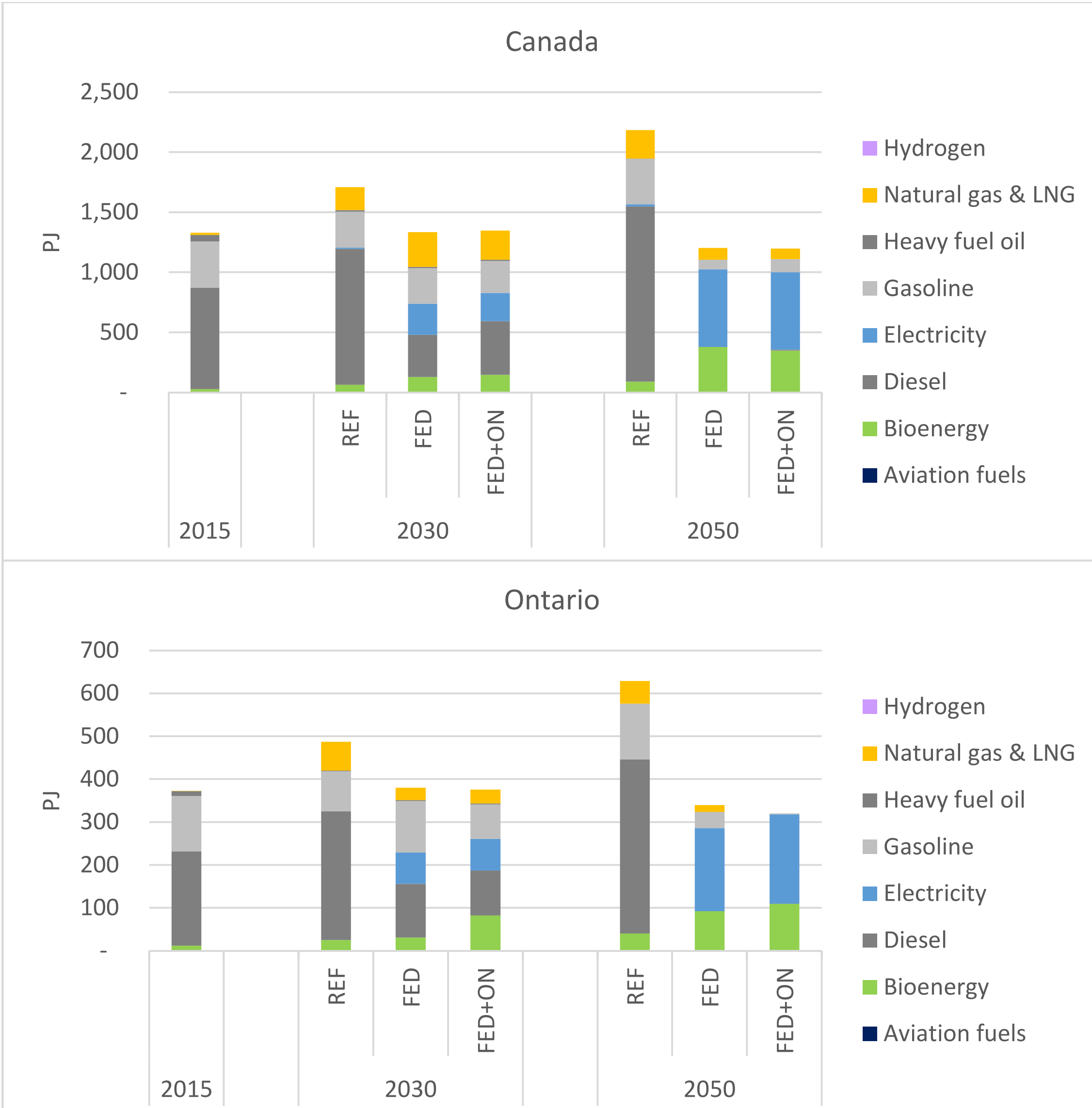
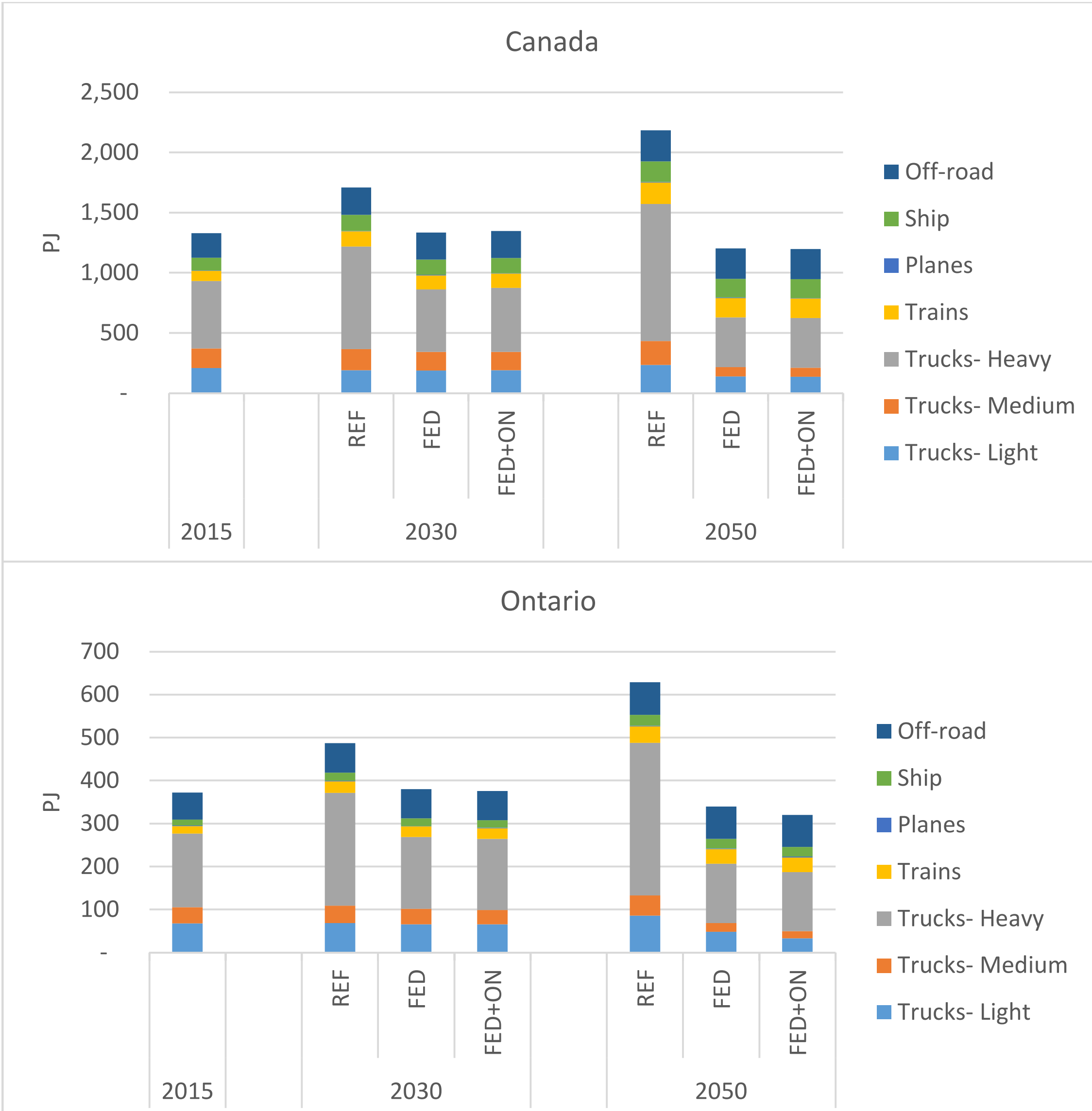


Figure 24. Final energy consumption by mode – Freight transport



6.6 Buildings sector

Summary results for GHG emissions from the buildings sector for the three scenarios are shown on Figures 25 and 26. Key observations from a detailed review of the background documentation and results are as follows:

- Energy consumption for buildings (residential and commercial) for all of Canada was 2,793 PJ in 2015. Of this amount, 1,600 PJ (57%) was from burning fossil fuels (dominantly natural gas), primarily for producing thermal energy for space heating, for hot water and steam production, and cooking (Figure 26). Some thermal energy was also obtained from bioenergy and electricity. The other energy uses in buildings include appliances, computers, controls, etc. which are dominantly supplied by electricity.

- Energy consumption in buildings remains relatively constant. For all of Canada, for the REF scenario, energy consumption would decline from 2,793 PJ in 2015, to 2,729 PJ in

2030, and then increase to 3,038 PJ in 2050. The dominant reduction is associated with energy conservation, which occurs almost immediately in the minimum cost solution (see below)

For Ontario, the corresponding numbers are 991 PJ in 2015, declining to 938 PJ in 2030, and then increasing to 1032 PJ in 2050.

- It is of special note that the above numbers include energy conservation. With implementing existing cost efficient options for energy conservation, there is the potential to progressively reduce energy consumption in buildings. Furthermore, as demonstrated with the results of the REF scenario, it is more cost efficient to invest in energy conservation than to incur added costs in the buildings sector, as energy conservation is less costly than expenditures which are otherwise incurred as a consequence of not implementing readily available energy conservation programs. This places special emphasis on the importance of implementing the remaining energy conservation options, even in the absence of GHG mitigation considerations. A more comprehensive inventory of energy conservation measures would likely identify an even larger potential for cost-effective energy conservation.
- For the two mitigation scenarios, energy demand reduces modestly relative to the results of the REF scenario, and is relatively unchanged from energy consumption in 2015. However, there is a major change in the energy mix, with major reductions in the use of fossil fuels and large increases in the use of electricity. Electricity includes major increases in electricity from the grid, as well as substantial increases in solar PV installations.

  By 2050, there would be a virtually complete elimination of combustion emissions from buildings for all of Canada, including complete elimination of natural gas for space heating, hot water and steam production, and for cooking.
- It is important to note that some of the results are sensitive to cost and performance parameters. For example, there is a close cost competition between electric base-board heater and electrically driven air source heat pumps. Small change could result in substantial shifts in the solution mix, such as less baseboard heaters and more heat pumps. It is especially important that more detailed examinations be carried out with data that are more specific for Ontario, and including sensitivity analyses. Additional analyses should then be carried out for improving overall perspectives on the most cost effective options for transforming thermal energy systems in buildings, with available and evolving technologies and their associated costs.

Figure 25. Final energy consumption - Buildings

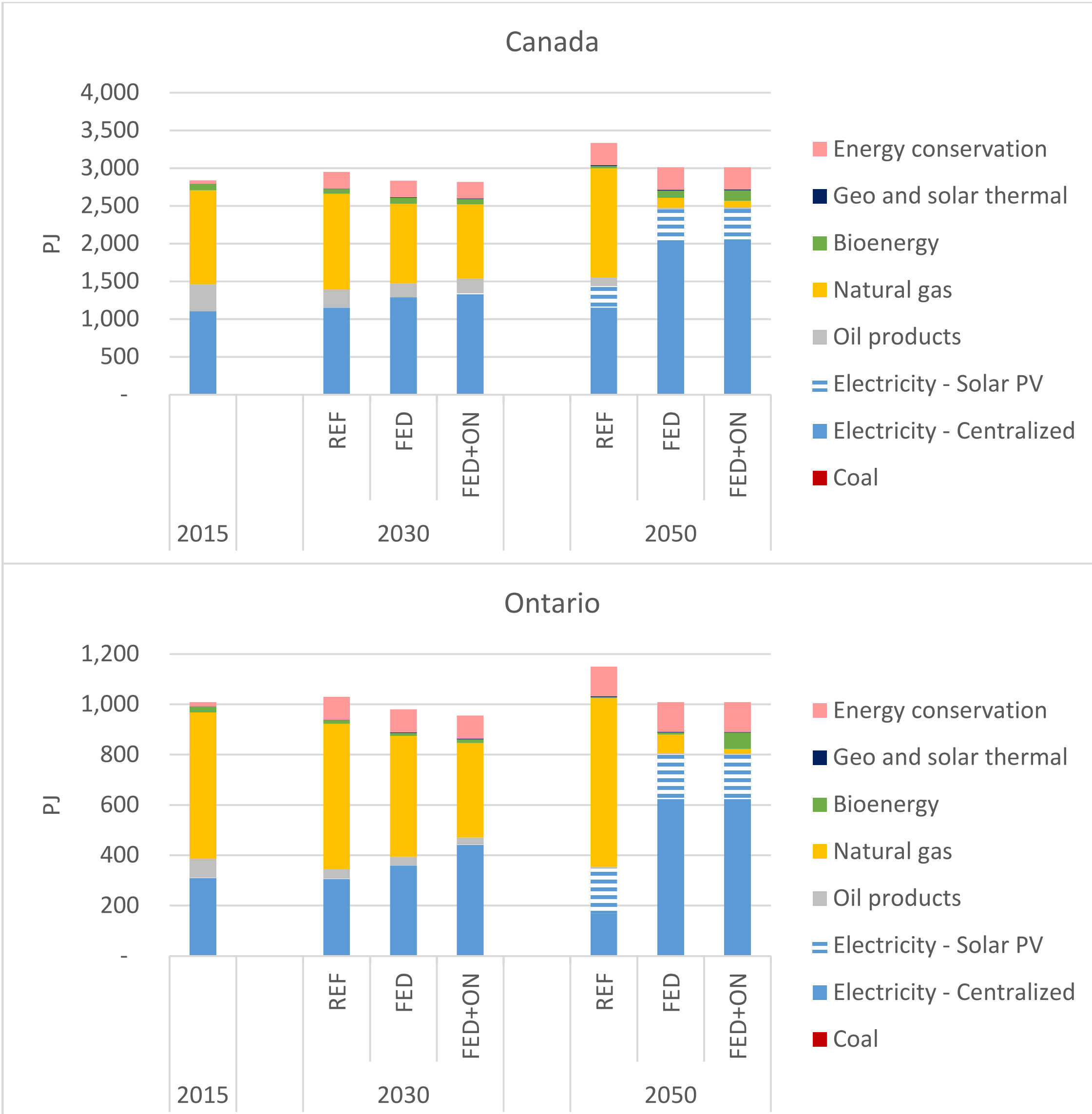
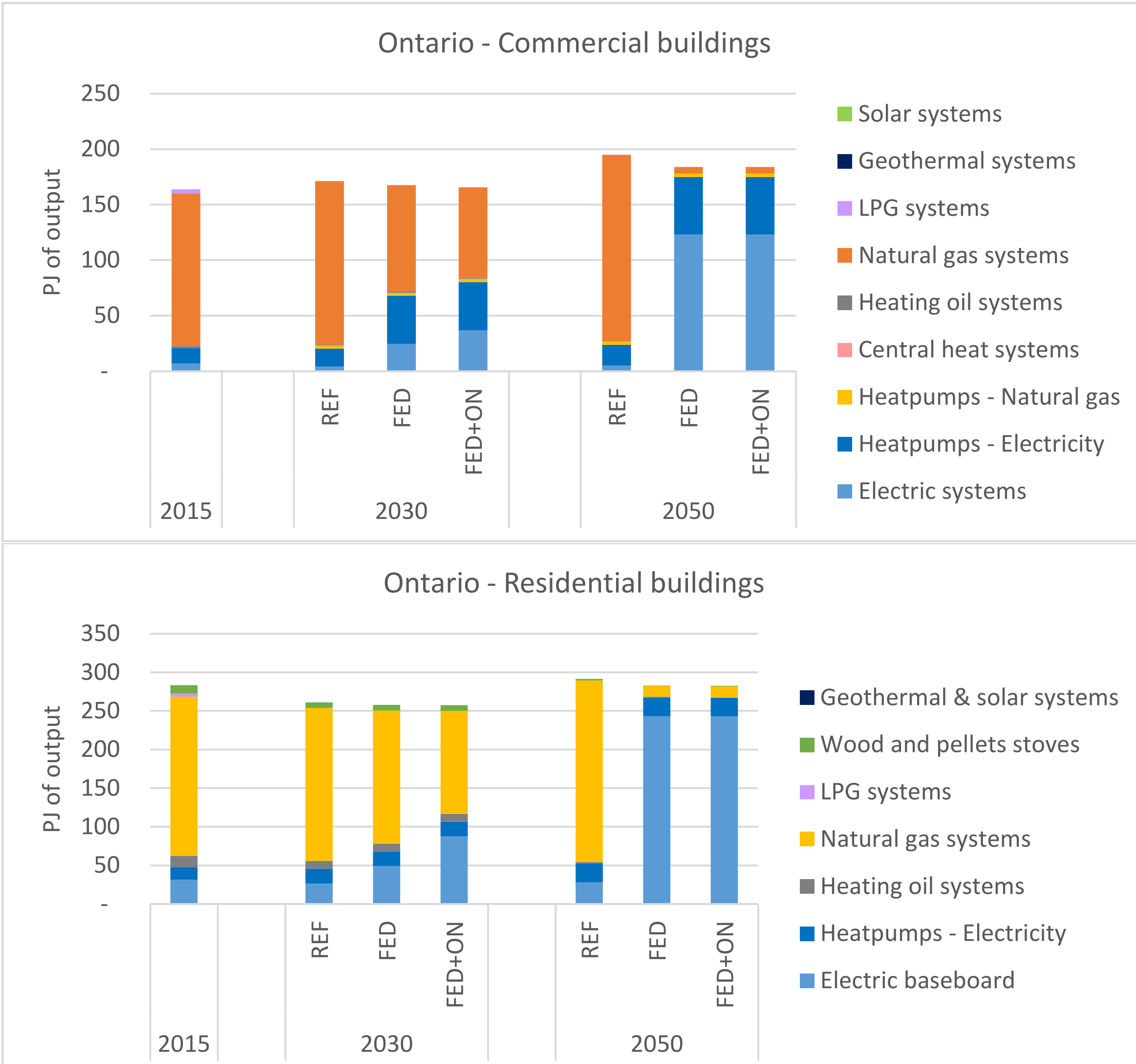


Figure 26. Market shares for space heating technologies



6.7 Industrial sector

Summary results for GHG emissions from the industrial sector for the three scenarios are shown on Figure 27. Key observations from a detailed review of the background documentation and results are as follows:

- As shown in Section 2.4, the industrial sector produces 13% of Canada's total GHG emissions. This includes 6% of combustion emissions and 7% of non-combustion emissions. The industrial sector produces 25% of Ontario's total emissions, including 10% of combustion emissions and 15% of non-combustion emissions.
- Energy demands for the industrial sector are projected to continue growing in Canada, including especially in Ontario. Results of the REF scenario show that energy demands for all of Canada increase from 2,160 PJ in 2015 to 2,873 PJ (33%) in 2030, and to 3,798 PJ (76%) in 2050.

For Ontario, projected increases are even more rapid; from 641 PJ in 2015, to 992 PJ (55%) in 2030, and to 1,391 PJ (117%) in 2050.

- The current energy mix for industrial sector energy consumption includes fossil fuels (50%), electricity (30%) and bioenergy (20%).

  For Ontario, there is a higher dependence on fossil fuels (66%). The other energy sources include electricity (25%) and bioenergy (10%).

- From the results of the REF scenario, there are only modest changes in the energy mix for all of Canada. Use of fossil fuels increases from 50% to 58%, while bioenergy declines from 20% to 11%. Electricity remains essentially unchanged.

  For Ontario, these trends are similar, with fossil fuels increasing form 66% to 70%, and bioenergy reducing from 10% to 5%.

- For the mitigation scenarios, there are only nominal reductions in combustion emissions, which are directly related to the rate of reducing reliance on the use of fossil fuels. For the FED scenario, combustion emissions increase slightly, from 65 Mt in 2015, to 68 Mt in 2030, and subsequently, decline to 46 Mt in 2050.

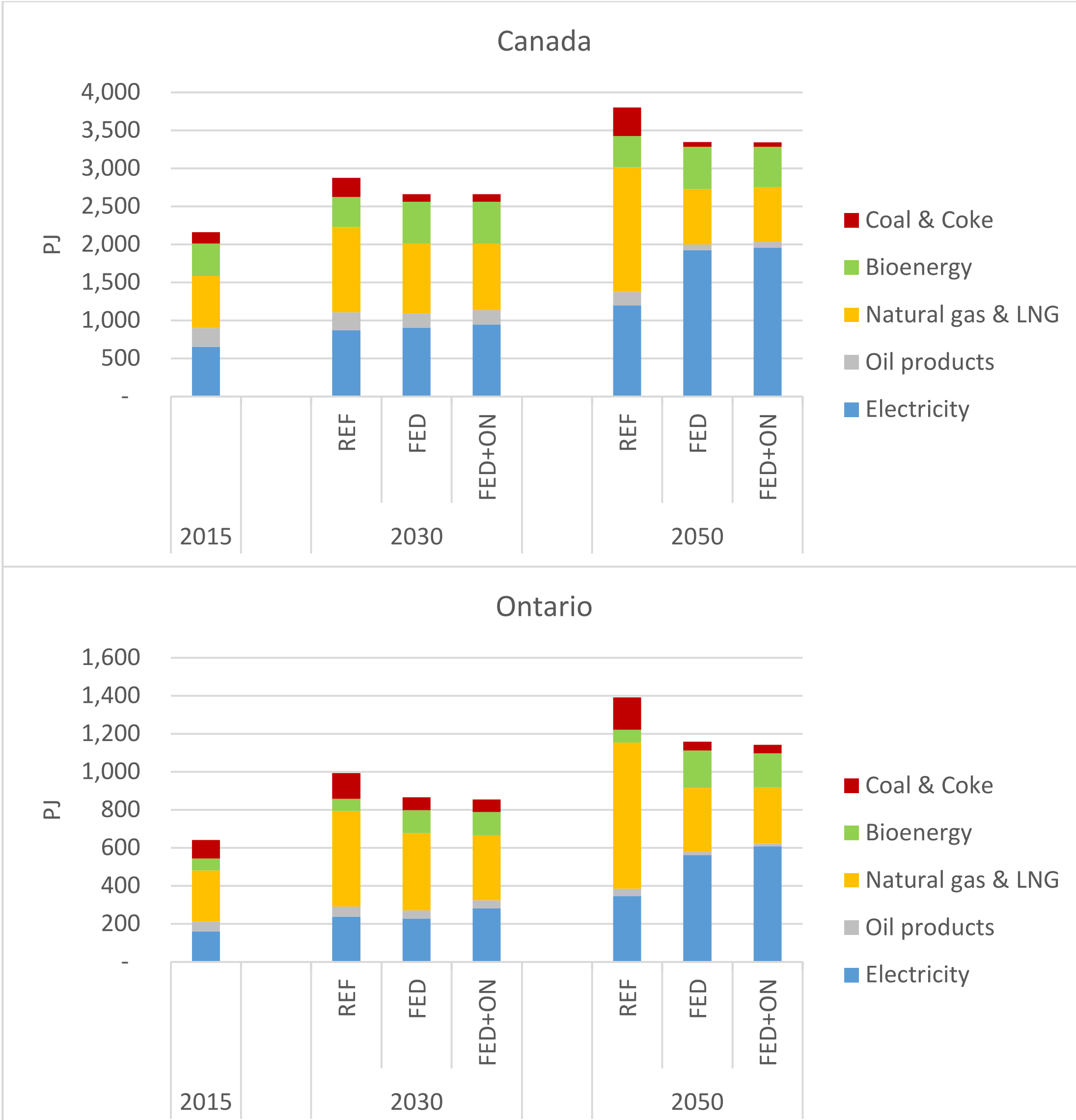
  For Ontario, the trend is similar. Combustion emissions increase from 26 Mt in 2015, to 30 Mt in 2030, and subsequently decline to 22 Mt in 2050.

  Results for the FED+ON scenario are similar, except that there is faster progress on reducing emissions for Ontario – to 16 Mt in 2030 and to 20 Mt in 2050.

- It is important to note that reducing emissions in the industrial sector is both complex and expensive. Production of thermal energy with electricity or bioenergy is substantially more expensive than with natural gas. Accordingly, when considering transformation strategies for the industrial sector to satisfy aggressive GHG mitigation targets, it is essential to include normal energy efficiency opportunities, such as heat recovery systems. However, it is also necessary to give consideration to process changes, and to new technologies, including carbon capture and storage, which are still in early stages of development.

  Because of complexities and costs for the industrial sector, results from this study indicate that by 2050 the industrial sector may become the dominant source of combustion emissions. For these reasons, it is especially important to carry out more detailed investigations of GHG mitigation options and strategies for the industrial sector, while ensuring that this sector remains globally competitive.

Figure 27. Final energy consumption – Industries



6.8 Trade balance for energy commodities

Summary results of the trade balance for energy commodities for the three scenarios are shown on Figure 28. Key observations from a detailed review of the background documentation and results are as follows:

- As noted in Section 5, Canada continues to be a net exporter of energy commodities, including fossil fuels, especially from jurisdictions with economies based on continuing production and export of fossil fuels, such as Alberta, Saskatchewan and Newfoundland & Labrador. Projections used in this study include updated information from the most recent National Energy Board report.

  For 2015, Canada's total net energy export was equivalent to 13,065 PJ The dominant exports included crude oil and oil products (5,167 PJ), uranium (5,079 PJ) and natural gas, including liquefied natural gas (LNG) (2,081 PJ). There were also net exports of coal, electricity and bioenergy.

- Ontario is a net importer of virtually all energy commodities except electricity. For 2015, net imports were equivalent to 3,507 PJ, dominated by crude oil and oil products (1,369 PJ), natural gas (959 PJ), uranium (1,082 PJ) and coal (152 PJ). Net electricity exports were 51 PJ.

- For the REF scenario, for all of Canada, it is projected that there will be a nominal increase in the net export of energy commodities, from 13,065 PJ in 2015, to 14,587 PJ in 2030, and to 15,473 PJ in 2050. The dominant change will be with crude oil and oil products. This increases from 5,167 PJ in 2015, to 9,482 PJ in 2030, and then only slightly further, to 9,725 PJ in 2050. The increase to 2030 reflects the impacts of additional committed oil-producing projects in Canada which are scheduled for on-line production before 2030.

  The other significant projected change for Canada includes additional exports of natural gas, including especially LNG. Total exports would increase from 2,081 PJ in 2015 to 3,060 PJ in 2050. Most of the increase would occur after 2030, as exports in 2030 are projected to decline to 776 PJ, due to reduced exports to the United States, as well as delays in developing supporting LNG infrastructure for exports to other markets, including especially Far East markets.

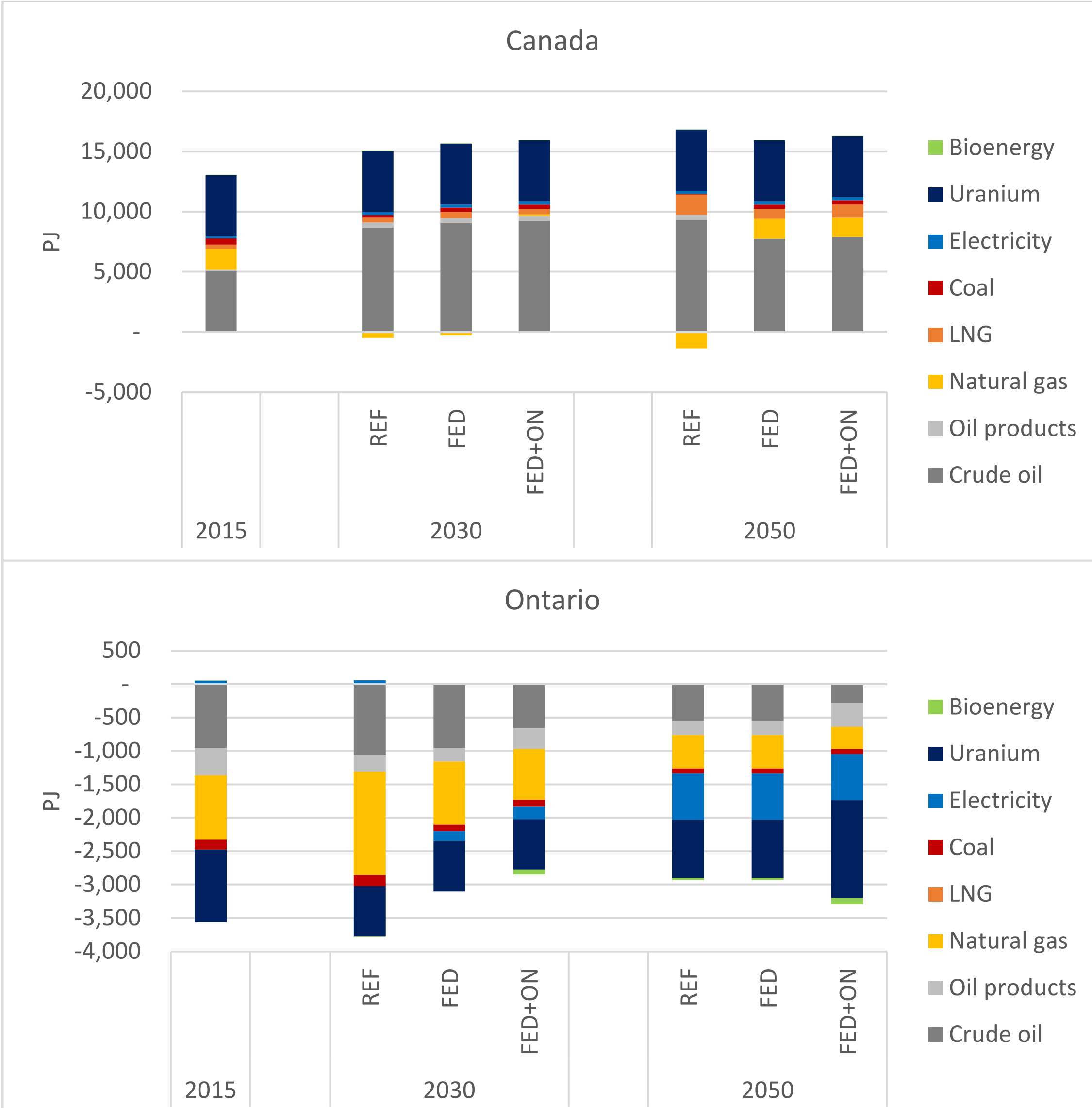
- For Ontario for the REF scenario, net imports of energy commodities increase to 2030, and then decline from 2030 to 2050. Net imports increase from 3,507 PJ in 2015, to 3,720 PJ in 2030 and then decline to 2,933 PJ in 2050. For the period to 2030, there is continuing growth in demand for fossil fuels, while demand for uranium declines. The electricity sector continues to be a minor net exporter of electrical energy.

  After 2030, however, there are major changes. With projected imports of electrical energy from Quebec (Section 6.3), the electricity sector transforms from being a net exporter of 55 PJ in 2030, to a net importer of 693 PJ in 2050. There are also associated reductions in the import of all fossil fuels during this period.

- For the two mitigation scenarios, there are modest increases in the amounts of net energy exported for all of Canada, relative to the REF scenario. Most of the increase in 2030 is due to additional exports of oil and oil products, which reflects the additional availability for exports as a consequence of reduced oil and gas use in Canada (coinciding with progress on GHG mitigation).

  For Ontario, there are significant reductions in imports of all fossil fuels relative to the REF scenario in 2030 – from 3,720 PJ for the REF scenario, to 3,106 PJ for the FED scenario, and 2,850 PJ for the FED+ON scenario. For 2050, there are only nominal differences in results for the three scenarios.

Figure 28. Commercial trade balance for energy commodities



6.9 Mitigation costs

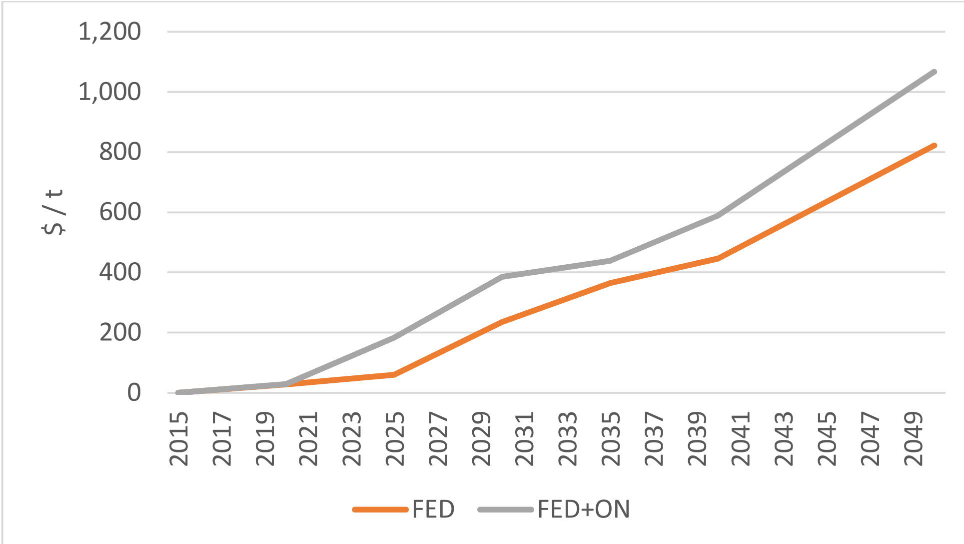
Summary results of mitigation costs for GHG emissions are shown on Figures 29. Key observations from a detailed review of the background documentation and results are as follows:

- The principal reporting measure was marginal cost, as derived by the optimization model. This is a direct measure of the lowest incremental cost for achieving a further unit of GHG reduction at the optimal solution. At the derived minimum cost solution, the unit cost of every available option for reducing GHG emissions is either equal to or greater than this derived marginal cost.

  This value has special significance when considering carbon pricing. Based on the assumption of perfect market responses, and with the goal of achieving GHG reduction results as reported in this study, the sequence of carbon prices over time would need to be equal to the derived marginal costs.

- With consideration of the previously noted comments, the key results are summarized as follows:
  - As expected, for any scenario, marginal costs increase over time. This arises as the lowest cost options for GHG mitigation are selected first, with future options being progressively more expensive.
  - Also, as expected, marginal costs are higher with increasingly stringent GHG emissions reduction targets. The imposition of the more stringent mitigation target for Ontario results in marginal costs, as well as overall costs, being higher for the FED+ON scenario, relative to the FED scenario.
  - It should be appreciated that marginal costs, as reported here, indicate costs (equivalent carbon prices) on the order of hundreds of dollars per tonne for CO_2 to achieve deep reductions in GHG emissions, and not tens of dollars per tonne, which has been the basis for carbon pricing frameworks in many jurisdictions. If carbon pricing is to be used as the dominant policy instrument for achieving GHG mitigation results, it is important to recognize that selected unit carbon values need to be generally aligned with such derived marginal costs.
  - An economic analysis of the adverse economic impacts that may be caused by climate change (or conversely, the economic benefits from avoiding some of these impacts due to mitigation) is outside the scope of this study. It is generally recognized that the consequences of uncontrolled climate change are likely to exceed the costs of taking action to mitigate these impacts.
- Additional analyses were carried out to assess the approximate costs for GHG mitigation as a function of GDP. Differential costs between the results of the REF scenario and each of the two mitigation scenarios on a year by year basis were used as the basis for this evaluation.
  - The results showed that the cost of GHG mitigation for all of Canada would be 1% of Canada's GDP in 2030, rising to 4% of GDP in 2050. Results for the two mitigation scenarios were similar.
  - With the FED scenario for Ontario, the cost for Ontario would be 0.9% of GDP in 2030, increasing to 2.6% of GDP in 2050.
  - Results for the FED+ON scenario were substantially higher for Ontario. The cost for Ontario would be 1.5% of GDP in 2030, rising to 3.4% of GDP in 2050.
  - It is important to appreciate that longer term costs can be subject to considerable variability and may turn out to be lower than costs derived in this study. Important options for the long term may come down in price, especially with mass production and technological refinements. There are also technology options that are relatively unknown or which can be greatly improved in terms of both performance and cost. For these reasons, it is important to exercise caution when interpreting options and costs for mitigation, especially for the long term.

Figure 29. Marginal abatement costs for Ontario



6.10 Principal Observations

Based on results of the three scenarios as reported in this section, the principal observations are as follows:

1. **Mitigation targets can be met**:

   The targets of achieving defined GHG emissions reduction targets in 2030 and 2050 for Canada, and for Ontario, can be met with existing proven and known emerging technologies. However, it is important to note that Ontario needs to increase its annual rate of mitigation, and to implement more aggressive mitigation programs, especially in the consumption sectors (transportation, buildings and industry).

2. **Energy conservation is the first option:**

   There are significant opportunities for reducing energy demand with existing energy conservation programs, even without any consideration of GHG mitigation. This is the most cost effective option for reducing energy costs, with early attention required for overcoming current institutional, administrative and other barriers.

3. **Pathways and priorities for mitigating combustion emissions in Ontario are as follows:**

   - Fully decarbonize the electricity supply
   - Foster early and rapid transformation of the transportation sector, dominantly with the electrification of road transport and urban public transportation systems, but also including bioenergy
   - Ensure early progress in decarbonizing the buildings and industrial sectors

4. **There are major changes in the energy supply mix for reducing combustion emissions:**

   For meeting combustion mitigation targets for all of Canada, the ratio of fossil fuels to electricity to bioenergy needs to change from 70%: 22%: 8% in 2015 to 19%: 64%: 16% in 2050. For Ontario, the corresponding change is from 77%: 18%: 5% in 2015, to 24%: 60%:

14% on 2050. This represents a three-fold increase in electricity demand and a doubling of bioenergy demand, while the use of fossil fuels reduces to less than one-third of current consumption.

5. **There is a need for major increases in electricity supply:**

   Electricity supply in Canada needs to increase from 677 TWh in 2015 to 2,324 TWh in 2050. Installed capacity needs to increase from 151 GW in 2015, to more than 700 GW in 2050. Correspondingly, for Ontario, electricity supply needs to increase form 154 TWh in 2015 to 461 TWh in 2050.

6. **The composition of electricity supply in Ontario needs to change:**

   The minimum cost solution for GHG mitigation includes major changes in Ontario's electricity supply system. The dominant changes include major development of renewables, including remaining hydro potential, more capacity at existing hydro sites, increases in intermittent renewables (wind and solar), more grid scale storage, such as pumped storage used to enhance dependable capacity, roof top solar for buildings, major grid interconnection with Quebec with associated electricity imports from Quebec, and nuclear generation.

7. **Transformation of the transportation sector is an immediate priority:**

   For reaching the 2030 mitigation target in Ontario, there is a need for immediate and sustained action on transforming the transportation sector. This sector produces 50% of Ontario's combustion emissions. Priority should be given to the electrification of road transport, including both passenger and heavy freight transport vehicles, and the electrification of public transportation systems in urban regions.

8. **Transformations for production of thermal energy in buildings need to progress quickly:**

   Fossil fuels are used in buildings primarily for space heating and for hot water and steam production. These fuels need to be replaced with an optimum combination of electrically driven heat pumps (both air source and geothermal), electric baseboard heaters, biogas, passive solar, thermal storage, improved insulation, etc. The buildings sector should be essentially fully decarbonized in Canada, and in Ontario, by 2050.

9. **There is need for early action on decarbonizing the industrial sector:**

   While this is a challenging sector for major reductions in combustion emissions, it is essential to make early progress in this sector as well. This may require special attention to achieving energy efficiency improvements, such as heat recovery systems, as well as process changes that result in reduced emissions, and development of storage technologies, including GHG capture and use (or reuse).

10. **Trade balance in energy commodities for Ontario will improve:**

    Canada is projected to continue being a major global exporter of energy commodities. However, for Ontario, the situation is different, with dependence on energy imports, dominantly fossil fuels, from other provinces in Canada and from the United States. This balance will improve as Ontario reduces its reliance on fossil fuels for energy-related needs.

11. **Costs for GHG mitigation are high:**

    Marginal costs for mitigating combustion emissions are typically hundreds of dollars per tonne of CO_2, not tens of dollars. This is substantially higher than has been reflected in current carbon pricing systems for GHG mitigation. The cost of reducing combustion emissions will increase progressively to approximately 1% of GDP in 2030. While there are expectations that such costs will continue to increase after 2030, there are also opportunities for reducing costs with new and more efficient technologies.

12. **Early action on non-combustion emissions and land use changes is important:**

    It is important to take early action on strategies to reduce non-combustion emissions and to develop land-based carbon sinks, especially in the forestry sector. These actions will be needed to offset GHG emissions that cannot be fully mitigated.

13. **There is a need for better information and data, and additional study on Ontario's mitigation challenge:**

    It is important to carry out additional investigations with better and more precise data and information for Ontario. This should include additional scenario studies and assessments of additional mitigation options, with associated performance parameters and costs. Examples include the potential role of hydrogen in the transportation sector; carbon capture, use and storage (CCUS) for both electricity supply and industrial mitigation; and process changes in industry.

7 Conclusions and Recommendations

7.1 Conclusions

Deriving minimum cost energy-GHG reduction solutions using techno-economic systems optimization models, such as NATEM, can play a valuable role in the development of comprehensive climate strategies. NATEM can be run for any combination of GHG reduction targets and policies, over any timeframe, and for any jurisdiction or combination of jurisdictions in Canada. The NATEM model enables important insights to be gained and promising emissions reduction pathways to be identified – ones that might not be fully assessed by other types of analyses.

The NATEM model does not prescribe or constrain the decisions that governments make on policies and programs to be implemented, but the results of the analyses highlight promising GHG mitigation pathways and related costs. Deviations from these pathways will increase the cost of achieving specified GHG reduction targets and timelines, but may be required for other economic, social, environmental or political reasons.

The analyses performed for the ECO using the NATEM model brings into focus some key messages for Ontario that the consultants for this study highlight below:

- The GHG emissions reductions achieved in Ontario from 2005 to 2016 (44 Mt) has been mostly due to phasing out the use of coal for electricity and heat production, which was essentially completed in 2016. This has been the largest single source of GHG mitigation in Canada, which has resulted in Ontario's emissions being 21.5% lower than in 2005. To reach the 2030 goal, it will be necessary to further decrease emissions by more than 2 Mt per annum. For reaching the additional 80% GHG emissions reduction goal by 2050, GHG emissions will have to continue decreasing by 4 Mt per annum from 2030 to 2050.
- Accomplishing the targets would require transformative changes in Ontario's entire energy system, including:
    - Moving Ontario's energy mix away from its current dependence on fossil fuels and replacing it with low-carbon electrification of the economy. The minimum cost pathway to 2050 shows fossil fuel use declining from 77% to less than 16% of energy end uses, and electricity increasing from 18% to more than 60%. The use of biomass & biofuels would increase from 5% to more than 15%. In essence, all of the remaining hydro potential in Ontario would be developed, including incremental hydro at existing sites, complemented by expanded use of low-cost intermittent renewables, and drawing on pumped hydro storage to enhance dependable capacity. In addition, major electricity imports would be required from Quebec, and based on current cost estimates (excluding disposal and risk), some nuclear power expansion would be included.
    - GHG emissions reductions from energy conservation and efficiency improvements have played an important role in holding primary energy use in Ontario relatively constant in the face of an expanding population, economy and per capita income. To meet future GHG reduction targets, these measures would have to be accelerated.
    - Major transformation of the transportation sector would be required, including the electrification of cars and light duty vehicles as well as heavy freight transport by road,

and the expansion of urban and inter-urban public transportation systems (buses, street cars, transit systems), bolstered by urban population densification (i.e., less need for vehicular transportation) and integrated multi-modal transportation planning.

- Transformation of the building sector would require replacing space heating and hot water and steam production (currently dominated by natural gas) with electricity and biofuels, complemented by improved air tightness and insulation in buildings.
- Within the industrial sector, a major shift would be required to the use of electric motors for motive power, wherever feasible, and production of thermal energy using electricity and biofuels. Energy efficiency options, including thermal (heat) recovery systems and more efficient equipment, production process changes and GHG capture options will also be required.
- Early attention would be given to defining options for reducing non-combustion emissions, and for expanding analytical capability for deriving minimum cost pathways that combine both combustion and non-combustion emissions.
- Extensive land-use changes would be required, including implementing long-term plans supporting afforestation, improved forest management, and the production of long-lived wood products as building materials.

7.2 Recommendations

The following recommendations are proposed by the consulting team:

1. This study was carried out over a short time frame and only considered two scenarios as well as a reference scenario (all using readily available information). In crafting a new climate strategy for Ontario, the government should address some of the study limitations, including:
   i. The need for an updated and consistent inventory on potential hydro resources in all provinces. The existing inventory is old, and needs to be updated.
   ii. The need for a comprehensive inventory of pumped storage capacity in all provinces, with associated costs for developing this option.
   iii. The need for more research (and accessibility of the research) on technologies and costs for transforming rail transport and modifying industrial processes. The NATEM model used generic information, which should be replaced with more accurate information on GHG mitigation options pertinent to Ontario.
2. The analysis carried out for this study should be expanded to encompass a broader range of scenarios, which would enhance understanding of the most promising minimum-cost GHG reduction pathways for Ontario.
3. More in-depth assessments should be carried out on the benefits of greater integration of the Quebec-Ontario electricity supply systems. This option could lower the electricity production costs for both provinces (and reduce the amount of wasted *spill energy* in Ontario), while increasing the potential for adding low-cost intermittent generation supply (e.g., wind and solar) in a larger integrated system. It could also enhance joint export opportunities into U.S. electricity markets.

4. Immediate attention should be given to developing carbon sinks, especially in the forestry sector. Sinks will have increasing value over time as options for GHG reduction become more expensive. They will also help address the problem that, based on current knowledge, industrial process emissions and non-combustion emissions from the agriculture sector cannot be fully eliminated and may become the dominant source of GHG emissions in the future. A carbon sink program for the forestry sector should be given early support, and it will require a long-term governmental commitment.
5. Some promising options for achieving major reductions in GHG emissions in Ontario are not well understood and should be actively researched, including:
   I. The potential for an increased role for hydrogen in the transportation and industrial sectors;
   II. Process changes in industry for reducing both combustion and process emissions;
   III. Carbon capture, use and storage (CCUS) potential for capturing emissions, for both thermal generation and for industrial process emissions;
   IV. Improved information on fugitive emissions and analyses on upstream impacts on supply and delivery of fossil fuels, especially natural gas.
6. While the NATEM model has been applied in this study for defining the most promising pathways for GHG mitigation in Ontario, the model can also be used to assess cost effectiveness of alternative strategies and policies for GHG mitigation. It is recommended that the process for selecting and assessing effectiveness of different strategies and policies by based on a more analytically rigorous approach and methodology, including use of the NATEM and other complementing mathematical models.