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Greenhouse gas emissions mitigation potential in the commercial and institutional sector

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ABSTRACT

This study was conducted to identify energy efficiency improvement options and assess these opportunities in terms of potential of energy savings and greenhouse gas (GHG) mitigation for the commercial and institutional sector. In addition, associated GHG abatement cost (GHGAC) curves were developed. A western Canadian province, Alberta, was selected for a case study. A model was developed in the Long-range Energy Alternatives Planning system (LEAP) with 23 energy efficiency improvement scenarios associated with space heating and cooling, lighting, auxiliary equipment, and water heating in the commercial and institutional sector. The scenarios analyzed in this study quantified the reduced demand in energy use and GHG emissions as well as the abatement costs for fast (2013–2030) and slow (2013–2050) penetration periods. Ground source heat pumps (GSHPs) and efficient boilers for space heating, efficient lighting, and high-insulation in building envelopes are identified as having significant potential for GHG mitigation and have low abatement costs. A cumulative GHG mitigation of 28 Mt and 55 Mt is achievable in the fast and slow penetration scenarios in the sector, respectively.

1. Introduction

Energy contributes to all socio-economic development indicators that enhance lifestyles the world over. However, energy production and consumption are responsible for a large environmental footprint through GHG emissions [1]. The commercial and institutional sector is one of five socio-economic sectors. The sector consumes energy largely through building heating and cooling, lighting, water heating, auxiliary operating equipment, and auxiliary drive motors [2]. Activities in the sector such as fossil fuel combustion, organic waste decomposition, water treatment, and the operation of air conditioning and refrigeration systems contribute GHG emissions in the form of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and fluorinated gases [3].

Commercial buildings consume 40% of the world's energy annually and are responsible for 30% of the emissions related to energy consumption. Between 1971 and 2004, GHG emissions from commercial buildings increased by 2.5% per annum [4]. Commercial sector building energy consumption grew globally by 67% between 1980 and 2010 (from 17.54 EJ to 29.29 EJ) [5,6]. In the U.S. between 1990 and 2009, commercial sector GHGs increased by 1.2% annually [7] and in 2013 accounted for 17% (1127 Mt CO_2 eq.) of emissions [8]. In 2014, 18.5% of energy consumption in the U.S. was commercial sector energy use [9]. In Canada in 2012, the commercial sector consumed 12% of the country's secondary energy and accounted for 10% (49.1 Mt CO_2e) of the country's GHG emissions, which is 3.58% higher than the emissions in the 1990s [10].

Commercial energy demand is increasing as the world's population grows and, along with it, urbanization. In 2010, the commercial sector consumed 22% less energy than the residential sector; however, it grew more than three times faster between 1990 and 2010 [11]. Most of the energy in the commercial sector is consumed through space heating. The sector includes the activities associated with public administration, finance, trade, real estate, education, and commercial services. In Canada, retail trade, offices, and educational services make up 70% of commercial space. Between 1990 and 2010, commercial floor space grew by 40.6% (from 509.9 to 717.1 million square meters) [11]. Energy consumption in the sector grew by 23.3% (from 867.0 to 1,069.2 PJ) between 1990 and

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Abbreviations: \$, Canadian dollar; AESO, Alberta electric system operator; bl, billion; CANSIM, Canadian socio-economic information management; CERI, Canadian Energy Research Institute; CFL, compact fluorescent; CFR, capital recovery factor; CH_4, methane; CO_2, carbon dioxide; CSE, cost of saved energy; eq., equivalent; GHG, greenhouse gas; GHGAC, GHG abatement cost; GJ, gigajoule; GSHP, ground source heat pump; kWh, kilowatt hour; LEAP, long-range energy alternatives planning system; Mt, metric tonne; N_2O, nitrous oxide; NEB, National Energy Board; NG, natural gas; NPV, net present value; NRC, natural resources Canada; PJ, petajoule; U.S., United States; VSD, variable speed drive.

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2012. The sector's GHG emissions, including the sector's demand and supply side emissions, grew by 3.6% during this time [12].

The integration of energy efficient technologies in the commercial sector along with an assessment of energy savings potential, GHG mitigation opportunities, and related abatement cost results can help decision makers formulate and implement policy options. A GHG abatement cost curve (GHGAC) is commonly considered an important policy tool to assess energy economics and GHG abatement options [13]. The results of a 2013 study using GHGAC curves in commercial sector buildings in Colombia showed that automated lighting has a high GHG mitigation potential and negative cost for both old and new commercial buildings [14]. The GHGAC curves help describe individual policy assessment of mitigation measures [15]. The Government of Canada has established the National Energy Code of Canada for Buildings 2011 requiring efficiency improvement of 25% above former building codes (the Model National Energy Code for Buildings 1997), for instance, and established new minimum targets for improvements in energy efficiency in new buildings [16]. In the UK, according to revised regulations (2010), buildings must reduce CO_2 emissions to 25% below the 2006 regulations on average [17]. Further investigation is required to reach targets in energy efficiency for existing commercial and institutional sector buildings. The commercial and institutional sector in Alberta was selected for a case study on energy efficiency improvement and greenhouse gas emissions mitigation potential.

Secondary energy demand in Alberta's commercial sector in 2012 was 184.6 PJ, about 8.4% of the province's total energy demand (2200 PJ) [18]. Energy demand in the commercial sector increased by 35% (48 PJ) between 1990 and 2012. In 2012, GHG emissions from Alberta's commercial sector reached 5.8 million tonnes (Mt) CO_2 eq. Energy intensity that same year was 1.64 GJ/m^2, about 15% above Canada's average energy intensity of 1.43 GJ/m^2 in the commercial sector. The energy intensity data indicate that there is a room for improvement in Alberta's commercial sector energy intensity.

Different models have been used to derive GHGAC curves, although various studies reported weaknesses in those GHGAC curves, for instance with a mathematical prediction model for China's building sector to 2030 [13], eQuest and the LEAP model for commercial buildings in Colombia to 2040 [14], the TIMES_PT optimization model for CO_2 abatement in Portugal [19], the MARKAL-MACRO model for China's energy sector [20], the POLES model for OECD countries' Kyoto target reduction [21], and McKinsey's global cost curve for 2030 [22]. A review of the literature in the area shows gaps in knowledge in the commercial/institutional sector worldwide, particularly in terms of reducing energy intensity and GHG emissions, and also with respect to economic aspects. The previous studies show energy saving and mitigation cost in different geographical locations but do not consider the energy consuming pattern in Alberta's commercial and institutional sector and do not reflect the associated GHGAC curves. Those gaps are addressed in the present study.

The overall aims of this study are to assess a set of energy efficiency improvement and GHG emission reduction scenarios and to develop GHGAC curves for GHG emissions mitigation in the commercial and institutional sector.

The overall objective of this paper is to conduct a comprehensive assessment and development of GHG abatement cost curves for Alberta commercial and institutional sector using the Long-range Energy Alternatives Planning System (LEAP) model. The specific objectives are to:

- Identify energy savings options in the commercial and institutional sector,
- Assess the energy savings potential for the identified energy saving options using the LEAP model,
- Assess the GHG mitigation potential for the identified energy efficiency options using the LEAP model,
- Assess the associated GHG mitigation for the identified energy efficiency options, and
- Develop a cost curve to assess and prioritize the energy saving options based on both GHG mitigation potential and associated cost.

2. Methodology

Alberta's commercial and institutional sector has seven energy-consuming categories: (i) building space heating, (ii) water heating, (iii) auxiliary use equipment, (iv) auxiliary drive motors, (v) building lighting, (vi) space cooling, and (vii) street lighting. Energy-consuming units are identified within each category. We developed several scenarios with the aim of improving energy intensity in these categories. Our approach was as follows: we developed the LEAP model and from that derived GHGAC curves and evaluated the cost of saved energy (CSE) for each scenario. To determine the impact of individual improvement options, we modelled CSEs in LEAP. A discount rate of 5% and a specific lifetime were considered for a specific improved technology. Current energy prices and future price forecasts for Alberta are considered in estimating the CSE (see Table A1) [23,24]. Some of the data used in this study are considered based on the economic conditions in Alberta and Canada (see Table A2), and these data form the base case, hereafter referred to as the reference scenario.

2.1. The use of the LEAP model to evaluate GHG mitigation scenarios

LEAP is an energy policy and forecasting analysis software tool developed by the Stockholm Environment Institute based in Sweden. It has a bottom-up approach structure and the ability to capture all energy aspects. It has four modules: Demand, Transformation, Resources, and the Technology and Environmental Database (TED). LEAP is an integrated planning tool that can be used to track the energy consumption and GHG emissions for energy use, production, and extraction of resources in all economic sectors. It provides cost-benefit analysis results for each energy technology in the demand and transformation modules. The LEAP model is described in more detail elsewhere [1,25–28]. It has been used for energy system planning [29,30], energy demand by sector [31,32], and GHG emissions mitigation analysis [33–35].

The Alberta-specific LEAP model was developed based on publicly available data issued by the Alberta Electric System Operator (AESO) [36], the Canadian Energy Research Institute (CERI) [37], the National Energy Board (NEB) [38], and Natural Resources Canada (NRC) [39], as well as data found in Statistics Canada's CANSIM tables [40] and elsewhere.

2.2. Scenario development

2.2.1. Reference scenario

The reference scenario was developed based on the existing demand side energy intensity in Alberta's commercial and institutional sector. The input data for the model were taken from Natural Resources Canada's comprehensive energy use database [18]. Energy end-use forecasts were calculated based on Alberta's and Canada's socio-economic indicators with respect to gross domestic product (GDP), population, and technological improvements in end-use devices in Alberta's commercial and institutional sector. The province's population growth was considered to be 1% in the reference scenario [41,42] and 2005 was used at the base

Table 1
Energy intensities in the commercial and institutional sector reference scenario.

End-use categories	Reduction in the energy intensity in the reference case by the end of the scenario period
Space heating	5%
Space cooling	5%
Water heating	10%
Lighting	15%
Auxiliary equipment and motors	15%

year. Reference scenario energy demand was calculated based on historical trends for the period 1990–2009 and on the evaluation of trends from sources such as the NEB and NRC. The total area of Alberta's commercial and institutional sector was assumed to be 93.90 million m^3 [43] in the base year with an annual growth rate of 2.2% [43]. There are several categories of end-use technologies used in the sector. For a better understanding of energy consumption and GHG emissions in the sector, the sector was divided into five end-use categories: space heating, space cooling, water heating, lighting, and auxiliary equipment and motors. In the reference scenario, energy intensities drop over time as improved technology penetration levels increased in different end-use categories (see Table 1). The reference scenario provides a base, allowing us to compare the impact of efficient technology scenarios.

Alberta's reference scenario, also referred to as the business-as-usual scenario, describes, in this paper, the demand and supply of energy from 2010 to 2050. The end-use energy-intensity values are taken from Statistics Canada and the Natural Resources Canada Office of Energy Efficiency (NRC-OEE). The projected values of energy demand and supply and GHG emissions are calculated through the LEAP model based on historical trends. Tables A3 and A4 in the Appendix show final energy required by sub-sector and fuel type, respectively, in the reference scenario. Table A5 shows GHG emissions in the reference scenario as generated in LEAP. The results from the LEAP model were validated by comparing them with the commercial and institutional sector's available energy demand from Statistics Canada. As shown in Fig. 1, the modelled results are quite close to the actual demand and build confidence in the model.

2.2.2. New scenario development

Several scenarios were developed in each end-use category and are discussed in the following sub-sections. The scenarios were evaluated for two periods of growth. The model considers both a fast penetration case (2013–2030) and a slow penetration (2013–2050) case. In the commercial sector, penetration levels for various scenarios in each of end-use sub-category over time were considered to be low (15%–30%), medium (50%–65%), or high (80%–90%) based on the type of technology [44,45]. As the stock of improved technologies rises, the stock of existing technologies decreases. Various assumptions (efficiency improvement, technology penetration rate, cost of saved energy, etc.) for each of new scenario were entered into the LEAP model and are listed in Table 2. The devices chosen as the new options in each scenario were modeled in LEAP in order to assess GHG emissions reduction potential. The energy efficiency improvement potential for end-use devices is the key parameter that impacts GHG emissions reduction potential. Levels of energy efficiency improvement potential for new scenarios were selected based on technological improvements and guidelines from various sources [44,46–51]. Improvement in energy efficiency was assumed carefully considering the thermodynamic limit that can be achieved.

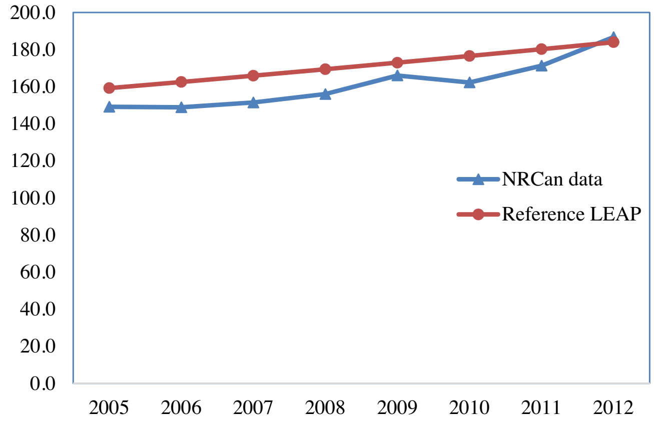


Fig. 1. Actual energy demand compared with LEAP model results.

2.2.2.1. Space heating scenarios. We reviewed and analyzed several technologies used for space heating in Alberta's commercial and institutional sector. Space is heated with a natural gas furnace or an electric heater. Another way to heat is by conserving the building's own heat. We identified eight areas (listed in Table 2) in which to improve the efficiency of space heating technologies and reduce GHG emissions. These sub-categories reflect several means of improving, modifying, or replacing end-use devices such as replacing existing technology with new technology, installing renewable energy use technology (i.e., ground source heat pumps), and improving the building envelope.

The improvement potential in energy intensity for new scenarios in space heating is assumed to be in the range of 6%–80% [52] based on the type of technology by the end of each study period (Table 2). An option for the replacement of natural gas furnaces by ground source heat pumps as GSHPs use renewable energy was assessed. Stock levels for existing and efficient technologies (except ground source heat pumps) were 95% and 5% by the end of each study period, respectively; and penetration levels of improved technologies increased to 65% (a medium level) by the end of each study period; accordingly, the existing stock declined to 35%. The stock of ground source heat pumps increased from 1% to 15% (a low level) by the end of each study period, however, and accordingly existing stock declined from 99% to 85% (Table 2).

2.2.2.2. Water heating scenarios. We studied several commercial sector water heating devices and developed scenarios for four (for each study period): high-efficiency water heaters, tankless water heaters, condensing water heaters, and waste heat recovery technologies (see Table 2). Energy intensity improvement potential levels were assumed to be 10%, 15%, 30%, and 18% for high-efficiency water heaters, tankless water heaters, condensing water heaters, and waste heat recovery options, respectively. Penetration levels increased from 5% to 65% for all improved options considered in this area; and existing stock declined from 95% to 35% accordingly (see Table 2).

2.2.2.3. Space cooling scenarios. Four space cooling technologies in which there is potential to improve energy intensity were chosen: GSHP space cooling, rooftop air conditioning, high-efficiency chiller, and cooling systems with high precision accessories (refrigerant valves, blower speed controller, and efficient motor). The energy intensities of these scenarios reduced in the range of 25%–50% (see Table 2). The high and low reduction in energy intensities were for rooftop air conditioning and high-efficiency chillers. Stock levels (except in the GSHP scenario) increased from 5% to 65% by the end of each study period. The GSHP scenario stock increased

Table 2
Assumptions and input data for the developed scenarios.

Scenario description	Energy intensity reduction by 2030/2050	Penetration level			
		Existing stock		Efficient stock	
		2010	2030/2050	2010	2030/2050
Energy saving options for space heating					
1. SH01: High-efficiency furnace with vent dampers	10%	95%	35%	5%	65%
2. SH02: High-efficiency condensing boiler	13%	95%	35%	5%	65%
3. SH03: Ground source heat pump (replacing electric furnace)	50%	99%	85%	1%	15%
4. SH04: Ground source heat pump (replacing NG furnace)	80%	99%	85%	1%	15%
5. SH05: Building envelope – high-level ceiling insulation	6%	95%	35%	5%	65%
6. SH06: Building envelope- high-level wall insulation	15%	95%	35%	5%	65%
7. SH07: Building envelope – high-level window insulation	6%	95%	35%	5%	65%
8. SH08: Building envelope – ventilation insulation	20%	95%	35%	5%	65%
Energy saving options for water heating					
9. WH01: High-efficiency water heater	10%	95%	35%	5%	65%
10. WH02: Tankless water heater	15%	95%	35%	5%	65%
11. WH03: Condensing water heater	30%	95%	35%	5%	65%
12. WH04: Waste heat recovery	18%	95%	35%	5%	65%
Energy saving options for space cooling					
13. SC01: Ground source heat pump for space cooling	40%	99%	85%	1%	15%
14. SCO2: Rooftop air conditioning for space cooling	50%	95%	35%	5%	65%
15. SC03: High-efficiency chiller for space cooling	25%	95%	35%	5%	65%
16. SC04: Efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor	40%	95%	35%	5%	65%
Energy saving options for lighting					
17. L01: High-efficiency street lighting	50%	90%	10%	10%	90%
18. L02: CFL-T5 HO bulbs (LGHT1)	25%	90%	10%	10%	90%
19. L03: High-intensity discharge ballast (LGHT2)	35%	90%	10%	10%	90%
20. L04: Pulse-starting metal halide bulbs (LGHT3)	23%	90%	10%	10%	90%
Energy saving options for auxiliary equipment					
21. AUXE01: High-efficiency auxiliary equipment	30%	90%	10%	10%	90%
22. AUXE02: High-efficiency auxiliary motor	5%	95%	35%	5%	65%
23. AUXE03: Auxiliary motor with variable speed drive	40%	95%	35%	5%	65%

from 1% to 15%. The existing stock of all scenarios declined accordingly.

2.2.2.4. Lighting scenarios. There are two types of lighting in Alberta's commercial and institutional sector, building lighting and street lighting. With respect to building lighting, we assessed the replacement of existing bulbs with three alternatives: CFL-T5 HO bulbs, high-intensity discharge-ballast bulbs, and pulse-starting metal halide bulbs (see Table 1). With respect to street lighting, we evaluated the replacement of street lights with high-efficiency bulbs. The energy intensity reduction potential of in this area is in the range of 23%–50%. Efficient stock levels increased from 10% to 90% (a high level). Accordingly, existing stock dropped from 90% to 10%.

2.2.2.5. Auxiliary equipment scenarios. The auxiliary equipment used in Alberta's commercial and institutional sector includes computers, stoves, vending machines, printers, other office equipment, motors in various end-use applications, variable speed drives [52,53]. We considered three equipment improvement options: high-efficiency auxiliary equipment, high-efficiency auxiliary motor, and auxiliary motor with variable speed drive in order to assess the impact on GHG emissions. Considered energy intensity improvement potentials were 30%, 5%, and 40% for the three scenarios, respectively (see Table 2). Penetration levels of efficient stock increased from 10% to 90% for auxiliary equipment and from 5% to 65% for the other two scenarios.

2.3. *Cost of saved energy (CSE)*

The CSE is used to estimate the cost of a technology investment. We estimated the CSE for several new scenarios in the commercial and institutional sector. The value is given as \$/kWh or \$/GJ based on the characteristics of the technology [54–56]. The CSE was calculated based on the investment cost, the saved energy from the new technology, the annual saving from saved energy, the lifetime of the technology, and the discount rate, all of which are shown in Eq. (1):

$$\mathrm{CSE} = [\mathrm{I} \times \mathrm{CRF} - \mathrm{D} \times \mathrm{P}]/\mathrm{D} \tag{1}$$

where

I = Investment cost for new technology
D = Annual saved energy
P = Unit price of energy
CFR (capital recovery factor) = $[\mathrm{i} \times (1+\mathrm{i})^{\mathrm{n}}]/[(1+\mathrm{i})^{\mathrm{n}} - 1]$
i = discount rate

As stated earlier, energy intensity data for end-use devices were collected from different sources [42,57]. Broadly speaking, there are two types of buildings, old and new, and energy consumption (MJ/building) in new buildings is comparatively lower than in old ones. The energy intensities, capital cost, and lifetime for old and new buildings are listed in Table 3. These values were used to calculate the CSE for each end-use technology. The CSE values for developed scenarios were modeled in LEAP in order to forecast GHG mitigation costs for each end-use device by estimating the GHG emissions mitigation potential and developing marginal abatement cost curves for the developed scenarios.

Table 3
Assumptions data and calculated CSE values for the developed scenarios.

Scenario description	Energy intensity, GJ/building (Existing/New)	Capital cost, $/building	Lifetime, year	Cost of saved energy, $/kWh	
				2010–2030	2030–2050
Energy saving options for space heating					
1. SH01: High-efficiency furnace with vent dampers	4615/4576	1200[b]	18	−4.5[a]	−6.5[a]
2. SH02: High-efficiency condensing boiler	4615/4576	25000	25	−1.5[a]	−3.0[a]
3. SH03: Ground source heat pump (replacing electric furnace)	250/125	25000	25	−0.1	−0.2
4. SH04: Ground source heat pump (replacing NG furnace)	4615/1385	40000	25	−6.0	−7.0
5. SH05: Building envelope – high-level ceiling insulation	4600/4324	24000	35	−3.0[a]	−4.0[a]
6. SH06: Building envelope- high-level wall insulation	4600/3910	62500	35	−2.0[a]	−3.0[a]
7. SH07: Building envelope – high-level window insulation	4600/4324	5000[c]	35	−3.0[a]	−7.0[a]
8. SH08: Building envelope – ventilation insulation	4600/3680	20000	20	−5.0[a]	−6.0[a]
Energy saving options for water heating					
9. WH01: High-efficiency water heater	800/720	5000	20	−4.0[a]	−4.0[a]
10. WH02: Tankless water heater	800/680	5000	13	−3.0[a]	−0.50[a]
11. WH03: Condensing water heater	800/560	2500	13	−6.0[a]	−7.0[a]
12. WH04: Waste heat recovery	800/656	5000	15	−4.0[a]	−5.0[a]
Energy saving options for space cooling					
13. SC01: Ground source heat pump for space cooling	200/120	50000	25	−0.03	−0.08
14. SCO2: Rooftop air conditioning for space cooling	200/100	50000	20	−0.02	−0.08
15. SC03: High-efficiency chiller for space cooling	200/140	40000	20	−0.05	−0.08
16. SC04: Efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor	675/405	20000	15	−0.02	−0.08
Energy saving options for lighting					
17. L01: High-efficiency street lighting	100/30	8000	5	−0.01	−0.05
18. L02: CFL-T5 HO bulbs (LGHT1)	800/600	3000	8	−0.06	−0.08
19. L03: High-intensity discharge ballast (LGHT2)	800/520	6000	3	−0.05	−0.07
20. L04: Pulse-starting metal halide bulbs (LGHT3)	800/616	6200	8	−0.05	−0.06
Energy saving options for auxiliary equipment					
21. AUXE01: High-efficiency auxiliary equipment	850/595	20000	15	−0.08	−0.12
22. AUXE02: High-efficiency auxiliary motor	675/641	28800	15	−0.08	−0.12
23. AUXE03: Auxiliary motor with variable speed drive	200/120	29000	15	−0.10	−0.14

[a] $/GJ.
[b] $/furnace.
[c] $/household.

2.4. Cost-benefit analysis

We simulated an integrated social cost-benefit analysis on the scenarios developed through LEAP and analyzed the GHGAC for each scenario in relation to the reference scenario. The LEAP model calculates the cost-benefit based on the costs of each part of the energy system in the demand and transformation modules. Key cost inputs include capital costs, operating and maintenance costs, and costs incurred for primary resource extraction and from importing and exporting fuels. The net present value (NPV) is estimated over both scenario periods at a discount rate of 5%, and cumulative GHG emission abatement costs are calculated as well.

3. Results

We developed 46 different scenarios (23 for each study period) for energy improvement in the commercial and institutional sector, as discussed in Section 2. We evaluated those scenarios compared with the business-as-usual scenario to assess energy saving and GHG mitigation potential as well as GHG abatement cost. The results of the improved scenarios are discussed in the following subsections and summarized in Table 4.

3.1. Energy saving options for space heating

In the space heating subsector, we assessed 16 energy efficiency options (8 for each study period), and calculated the energy saving potential as well as associated GHG emission reduction over timeframe (see Table 4). The results show a wide range of energy saving potential among the various technology options. For example, during the slow penetration scenario (2013–2050), scenario SH04: ground source heat pump (replacing NG furnace) exhibits the biggest energy saving (365 PJ) and GHG emission reduction (19 Mt CO_2 eq.) potential, whereas scenario SH03: ground source heat pump (replacing electric furnace) shows the smallest energy savings (12 PJ) and GHG emission reduction (0.8 Mt CO_2 eq.) potential. Similar results are also observed during the fast penetration period (2013–20130).

During the 2030 scenario period, cumulative energy savings were calculated to be 204 PJ and 114.9 PJ for ground source heat pump (replacing NG furnace) and building envelope – high-level wall insulation, respectively. For the 2050 scenario, the energy savings potential are 1.8 and 2.5 times higher than the 2030 scenario, respectively. The third largest potential energy saving option is high-efficiency condensing boiler for space heating, for a cumulative reduced energy consumption of 98.43 PJ and 245 PJ by 2030 and 2050, respectively.

In terms of GHG mitigation potential, the ground source heat pump (replacing NG furnace) offers a cumulative 8 and 19 Mt CO_2 eq. for the 2030 and 2050 scenarios, respectively. As usual, for both the 2030 and 2050 scenarios, building envelope – high-level wall insulation and high-efficiency condensing boiler are the second and third largest alternative scenarios for GHG mitigation potential, with savings of 6.43 and 5.49 Mt CO_2 eq. (for the 2030) and 16.2 and 13.7 Mt CO_2 eq. (for the 2050), respectively.

Table 4
Summary of results of energy saving, GHG mitigation, and related costs for all scenarios.

Energy-efficiency improvement scenarios	Fast penetration scenario (2013–2030)				Slow penetration scenario (2013–2050)			
	Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference		Incremental NPV (billion $) & GHG abatement cost $/tonne of CO_2 eq.		Cumulative energy reduction, PJ & GHG mitigation, Mt compared to reference		Incremental NPV in billion $ and GHG abatement cost $/tonne of CO_2 eq.	
	Energy	GHG	NPV (bl)	$/tonne	Energy	GHG	NPV (bl)	$/tonne
1. SH01: High-efficiency furnace with vent dampers	34.95	1.95	−1.5	−815	74.8	4.2	−2.1	−514
2. SH02: High-efficiency condensing boiler	98.43	5.49	−0.73	−133	245.1	13.7	−0.9	−72
3. SH03: Ground source heat pump (replacing electric furnace)	6.06	0.5	−0.06	−104	12	0.8	−0.09	−111
4. SH04: Ground source heat pump (replacing NG furnace)	204	8	0.12	15	365	19	0.1	5
5. SH05: Building envelope – high-level ceiling insulation	40.65	2.27	−0.5	−211	90.1	5.0	−1.0	−217
6. SH06: Building envelope – high-level wall insulation	114.9	6.43	−0.78	−122	289.3	16.2	−1.3	−82
7. SH07: Building envelope – high-level window insulation	40.65	2.27	−0.96	−422	90.1	5.0	−2.1	−434
8. SH08: Building envelope – ventilation insulation	44.19	2.49	−0.26	−109	83.6	4.7	−0.45	−97
9. WH01: High-efficiency water heater	10.46	0.58	−0.10	−183	19.8	1.1	−0.24	−219
10. WH02: Tankless water heater	5.0	0.29	−0.07	−250	8.1	0.5	−0.086	−193
11. WH03: Condensing water heater	39.04	2.19	−0.223	−102	96.6	5.4	−0.38	−70
12. WH04: Waste heat recovery	21.88	1.23	−0.26	−214	50.5	2.8	−0.44	−157
13. SC01: Ground source heat pump for space cooling	1.82	0.19	−0.08	−400	4.0	0.3	−0.09	−324
14. SCO2: Rooftop air conditioning for space cooling	7.92	1.0	−0.06	−77	22.9	1.7	−0.1	−58
15. SC03: High-efficiency chiller – space cooling	4.34	0.45	−0.06	−145	13.3	1.0	−0.1	−108
16. SC04: Efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor	1.92	0.2	−0.13	−572	6.8	0.5	−0.19	−382
17. L01: High-efficiency street lighting	6.07	0.64	−0.026	−35	13.2	1.0	−0.03	−28
18. L02: CFL-T5 HO bulbs (LGHT1)	40	4	−1.6	−379	70	6	−2.1	−347
19. L03: High-intensity discharge-ballast (LGHT2)	63	7	−1.2	−186	137	11	−1.6	−146
20. L04: Pulse-starting metal halide bulbs (LGHT3)	35	4	−1.4	−367	60	5	−1.8	−355
21. AUXE01: High-efficiency auxiliary equipment	61.56	6.61	−2.1	−324	130.8	10.4	−3.5	−346
22. AUXE02: High-efficiency auxiliary motors	7.19	0.74	−0.7	−980	21.7	1.6	−1.6	−1000
23. AUXE03: Auxiliary motors with variable speed drive	49.41	5.25	−0.94	−180	135	10.3	−1.5	−150

The cost analysis in terms of incremental net present value (NPV) shows best energy savings option are not the most cost effective. Among the efficiency measures, the high-efficiency furnace with vent dampers shows a cost saving of $1.5 billion (a negative NPV), while the ground source heat pump (replacing NG furnace) option shows the highest energy savings with the highest cost (about $0.12 billion for the 2030 scenario). Similar results are observed for the 2050 scenario.

3.2. Energy saving options for water heating

In water heating subsector, we evaluated 8 energy efficiency scenarios (4 for each time period of study), and calculated associated cost for energy saving and GHG mitigation potential (see Table 4). The energy saving varies from a cumulative 5–39 PJ and 8–96 PJ by 2030 and 2050, respectively. In terms of GHG mitigation potential, bigger energy savings options show bigger GHG mitigation potential both for the 2030 and 2050 scenarios. On the other hand, the best energy saving and GHG mitigation options are not the best cost savings. For example, in the water heating subsector, the condensing water heater offers the best energy saving of 39 PJ and associated GHG emission reduction of 2.19 Mt CO_2 eq. with an incremental cost savings of $0.223 billion by 2030, while the waste heat recovery option offers energy savings of 21 PJ and associated GHG emission reduction of 1.23 Mt CO_2 eq. with the highest cost saving of $0.26 billion during the same period of time.

3.3. Energy saving options for space cooling

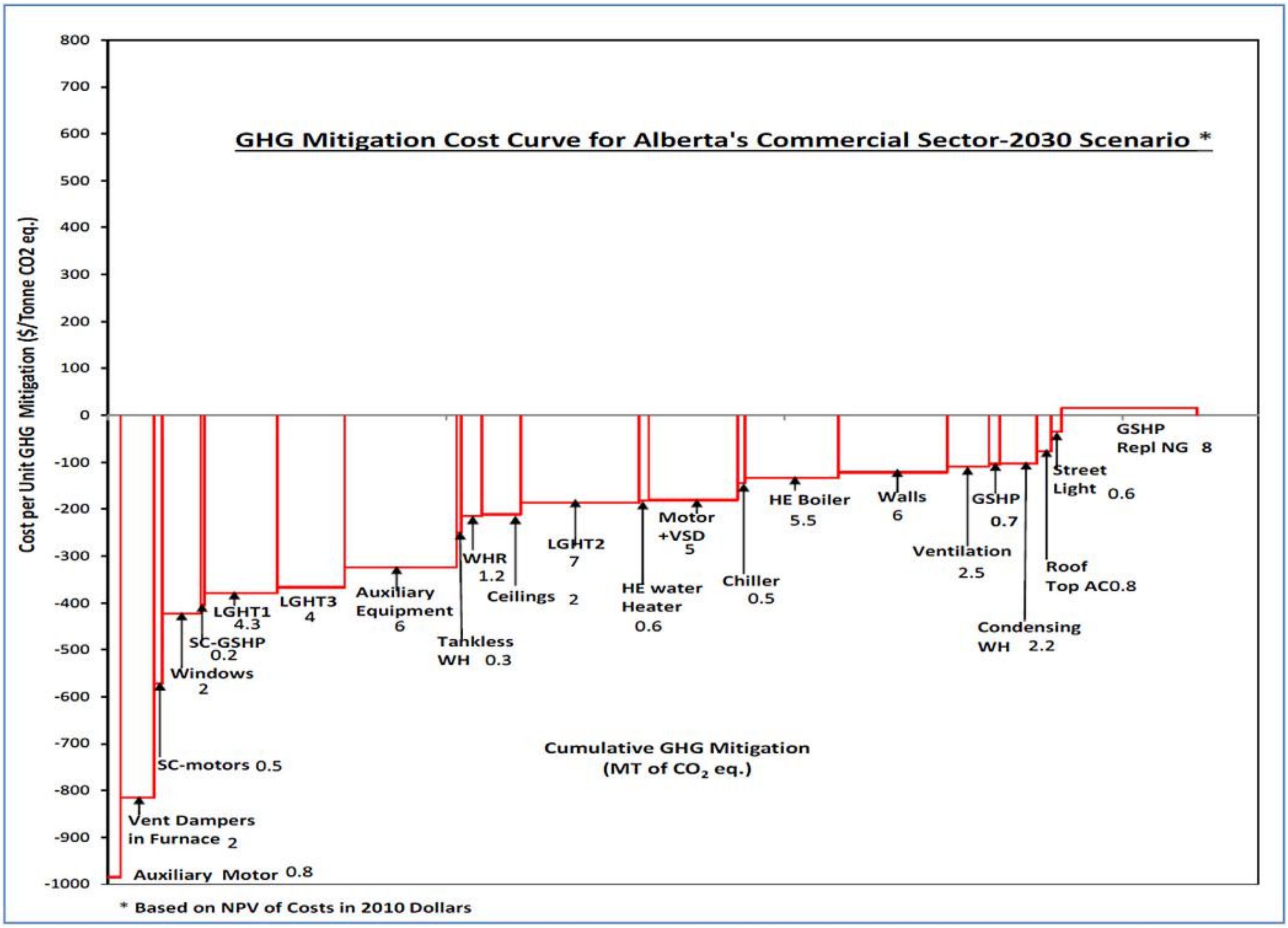
The model evaluated 8 energy efficiency improvement options (4 for each the slow and fast penetration phases) and estimated a cumulative reduction in electricity demand of 1.82–7.92 PJ and 4.0–22.9 PJ by 2030 and 2050, respectively, along with a cumulative reduction in GHG emissions of 0.2–1.0 Mt and 0.3–1.7 Mt by 2030 and 2050, respectively. In terms of energy saving and GHG reduction potential, the rooftop air conditioning and high-efficiency chiller options were found to be first and second in rank both for the 2030 and 2050 scenarios. While the results show the efficient space cooling design with precise refrigerant valves, blower speed controller, and efficient motor option is the most cost effective with a net incremental cost reduction of $0.13 billion and −$0.19 billion for the 2030 and 2050, respectively (see Table 4).

3.4. Energy saving options for lighting

The model estimated reduced demands in electricity for 8 scenarios (4 for each time period). One scenario was for efficient street lighting and the other three for building lighting. Among them, the LGHT2 scenario for building lighting reduces energy consumption of 5.7 and 5.8 PJ by 2030 and 2050, respectively (see Table 4).

3.5. Energy saving option for auxiliary equipment

In this sub-sector, high-efficiency auxiliary equipment, high-efficiency auxiliary motors, and auxiliary motors with variable speed drive options were evaluated, and with this information, we quantified the energy reduction and GHG mitigation potential for both the 2030 and 2050 scenarios. The high-efficiency auxiliary equipment and auxiliary motors with variable speed drive options show a cumulative energy reduction of 61.65 PJ and 49.41 PJ, respectively, by 2030, and 130.8 PJ and 135 PJ, respectively by 2050. The high-efficiency auxiliary equipment option also shows a cumulative GHG emissions reduction potential of 7 and 10 Mt CO_2 eq. by 2030 and 2050, respectively (see Table 4).



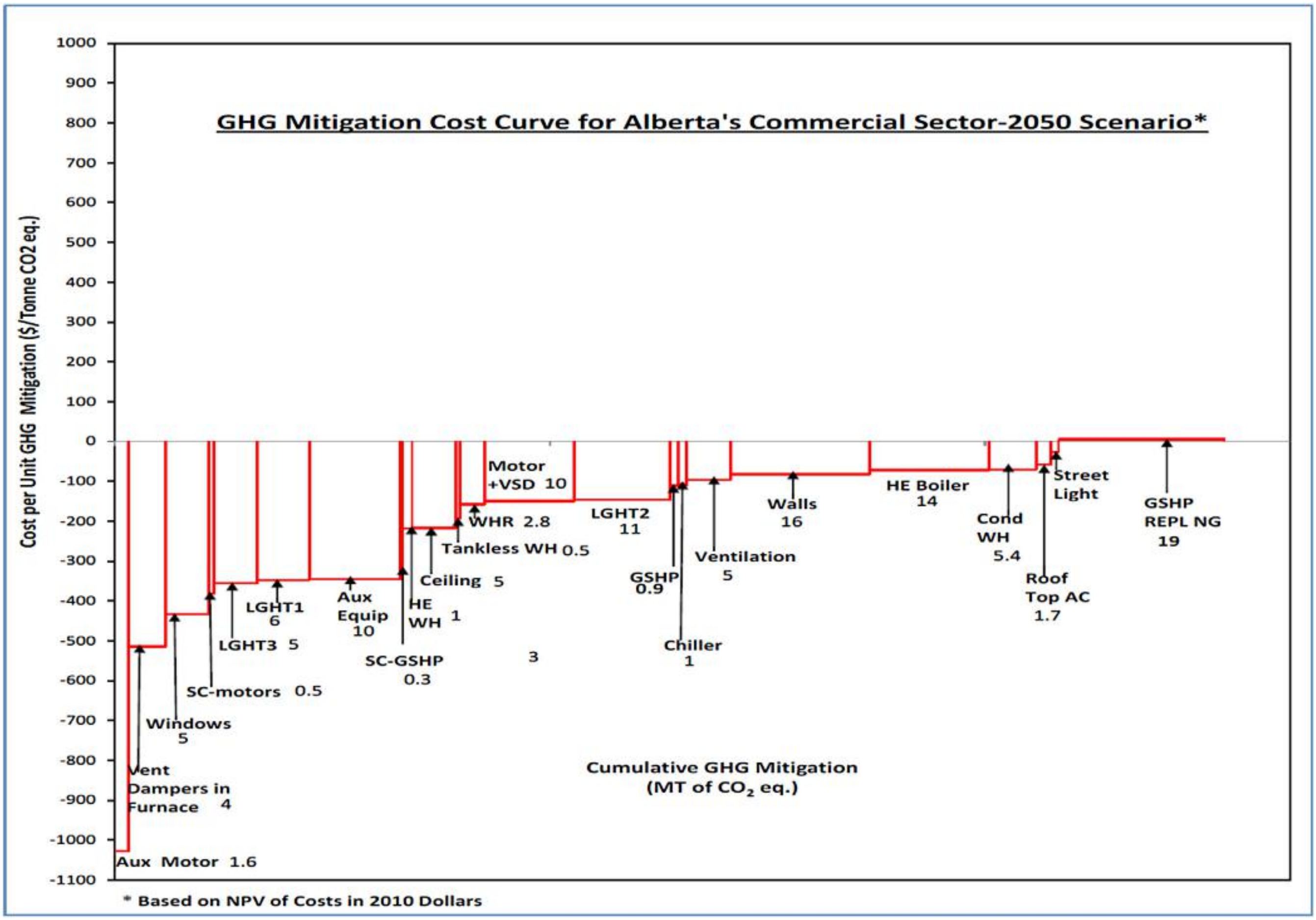
LEGENDS:

Auxiliary Equipment: High-efficiency auxiliary equipment
Auxiliary Motor: High-efficiency auxiliary motors
Ceiling: Building envelope – high-level ceiling insulation
Chiller: High-efficiency chiller – space cooling
Condensing WH: Condensing water heater
GSHP: Ground source heat pump(replacing electric furnace)
GSHP Repl NG: Ground source heat pump (replacing NG furnace)
HE Boiler: High-efficiency condensing boiler
HE Water Heater: High-efficiency water heater
LGHT1: CFL-T5 HO bulbs
LGHT2: High-intensity discharge-ballast
LGHT3: Pulse-starting metal halide bulbs
Motor+VSD: Auxiliary motors with variable speed drive
Roof Top AC: Rooftop air conditioning for space cooling
SC-GSHP: Ground source heat pump– for space cooling
SC-motors: Efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor
Street Light: High-efficiency street lighting
Tankless WH: Tankless water heater
Walls: Building envelope–high-level wall insulation
WHR: Waste heat recovery
Windows: Building envelope – high-level window insulation
Vent Dampers in Furnace: High-efficiency furnace with vent dampers
Ventilation: Building envelope – ventilation insulation

Fig. 2. GHG mitigation cost curve for Alberta's commercial and institutional sector for the fast penetration scenario (2013–2030).

4. Discussion

We developed GHGAC curves for every scenario in both fast and slow growth regimes. The cumulative GHG mitigation cost curves for both the 2013–2030 and 2013–2050 periods are shown in Figs. 2 and 3, respectively. The cost curves show the GHG (CO_2 equivalent in Mt) and abatement costs compared to the reference scenario. On the GHGAC curve, the horizontal axis represents total GHG abatement potential over the study time period, while the vertical axis shows associated costs per tonne of GHG emission reduction. All numbers above the horizontal axis represent a net investment required over the time period of study, while the numbers below the horizontal axis shows a net cost savings. More specifically, the width of each box (number affixed with the option shown in the figure) represents a cumulative GHG emission reduction potential over the time period for a particular option. For example, GSHP REPL NG 8 in Fig. 2 indicates that the ground source heat pump (replacing NG furnace) option could reduce GHG emissions by 8 Mt of by 2030; and the height of the same option shows a net investment of $15/tonne CO_2 eq. is needed to implement the



LEGENDS:

Aux Equip: High-efficiency auxiliary equipment
Aux Motor: High-efficiency auxiliary motors
Ceiling: Building envelope – high-level ceiling insulation
Chiller: High-efficiency chiller – space cooling
Cond WH: Condensing water heater
GSHP: Ground source heat pump(replacing electric furnace)
GSHP REPL NG: Ground source heat pump (replacing NG furnace)
HE Boiler: High-efficiency condensing boiler
HE WH: High-efficiency water heater
LGHT1: CFL-T5 HO bulbs
LGHT2: High-intensity discharge-ballast
LGHT3: Pulse-starting metal halide bulbs
Motor+VSD: Auxiliary motors with variable speed drive
Roof Top AC: Rooftop air conditioning for space cooling
SC-GSHP: Ground source heat pump– for space cooling
SC-motors: Efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor
Street Light: High-efficiency street lighting
Tankless WH: Tankless water heater
Walls: Building envelope–high-level wall insulation
WHR: Waste heat recovery
Windows: Building envelope – high-level window insulation
Vent Dampers in Furnace: High-efficiency furnace with vent dampers
Ventilation: Building envelope – ventilation insulation

Fig. 3. GHG mitigation cost curve for Alberta's commercial and institutional sector for the slow penetration scenario (2013–2050).

change. On the other hand, LGHT2 7 indicates the high-intensity discharge ballast option could reduce a cumulative 7 Mt of GHG emissions, while the height shows a negative cost of GHG emission reduction (−186 \$/tonne CO_2 eq.), indicating a net cost savings over the time period.

The estimated cost is the net present value of all cost components with the alternative technology and includes capital and operation and maintenance cost (in 2010 dollars). On the curves, the leftmost mitigation option shows the cheapest option and rightmost one shows the costliest. All mitigation options except ground source heat pump (replacing NG furnace) can be implemented with a negative GHG emission reduction cost. Here, the negative costs indicate benefits gained are higher than the cost incurred for implementing the GHG emission reduction measures. The high-efficiency condensing boiler, lighting, auxiliary equipment, building insulation, and auxiliary motors with variable speed drive scenarios show the highest potential for both GHG emissions mitigation and cost savings in both the fast and slow penetration cases.

Of the scenarios we developed, lighting with high-intensity discharge ballast showed high cumulative GHG mitigation potential in the fast growth market (7 Mt by 2030) and building envelope – high-level wall insulation showed the highest cumulative GHG mitigation potential in the slow growth market (16.2 Mt by 2050). In addition, the scenarios involving high-efficiency condensing boilers, lighting with high-intensity discharge-ballast, high-efficiency auxiliary equipment, and high-efficiency auxiliary motors with variable speed drive are identified as the most prominent options for GHG mitigation in the commercial and institutional sector in both the fast (5–7 Mt by 2030) and slow (5–16 Mt by 2050) penetration scenarios compared to the reference scenario. GHG mitigation costs for the sector are estimated to be in the range of −\$50 (by 2050) and −\$350 (by 2030) per Mt of CO_2 eq. mitigated. These estimates indicate that these options are economically attractive compared to the business-as-usual case. Combined total average GHG mitigation of 2–3 Mt/yr is achievable through energy efficiency improvement options in Alberta by 2030 based on the assumption that the options are implemented simultaneously. In a broad view, cumulative GHG mitigations of 28 Mt and 55 Mt are achievable in the fast and slow penetration scenarios in the sector, respectively, based on simultaneous implementation of the options. The efficiency-improvement scenarios show considerably more potential for both GHG mitigation and cost reduction than the business-as-usual scenario.

5. Conclusion

In this study we identified energy efficiency improvement options, GHG mitigation potential, and GHG abatement costs in the commercial and institutional sector of the western Canadian province of Alberta for both fast (2013–2030) and slow (2013–2050) market growth. Space heating and cooling, water heating, lighting, and auxiliary equipment are the main energy consuming sub-sectors in the commercial and institutional sector. Using a bottom-up approach in the LEAP model, we investigated improvement options in space cooling and heating, lighting, water heating, and equipment for auxiliary uses by developing 46 scenarios. Reduction in energy consumption, increased GHG mitigation potential, and marginal cost curves were assessed for all energy efficiency improvement scenarios. The results of alternate technologies' implementation both for 2030 and 2050 show that GHG abatement costs are negative, meaning a net cost savings would be achievable over the lifetime. The study from both time horizons indicates that the lighting, high-efficiency auxiliary equipment, high-level building wall insulation, and high-efficiency condensing furnace options play major role in GHG emission abatement in the sector. It is intended that the framework used in this study to analyze energy efficiency improvement and GHG mitigation scenarios along with financial considerations will help planners in other regions to develop commercial and institutional sector energy efficiency programs.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2017.02.007.

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