

DEVELOPMENT OF A FRAMEWORK FOR THE ASSESSMENT OF ENERGY DEMAND-BASED GREENHOUSE GAS MITIGATION OPTIONS FOR THE AGRICULTURE SECTOR



M. Bonyad, H. U. Shafique, M. A. H. Mondal, V. Subramanyam,
A. Kumar, M. Ahiduzzaman

ABSTRACT. *This study assesses greenhouse gas (GHG) mitigation options for the agriculture sector. The Long-range Energy Alternatives Planning (LEAP) model was used to develop a framework to assess future trends in energy demand and associated GHG emissions for the agriculture sector and to assess various GHG mitigation options associated with energy consumption. A business-as-usual (reference) scenario and 32 GHG mitigation scenarios were developed for the years 2009-2050 using the LEAP model. A case study for Alberta, Canada, was conducted. In the model, GHG mitigation scenarios were developed for the energy demand side (e.g., farm machines, farm transportation, lighting, and ventilation) based on efficiency improvements and the use of renewable energy. The mitigation scenarios were divided into two planning horizons based on technology penetration: slow penetration (2009-2050) and fast penetration (2009-2030). For each planning horizon, 16 scenarios were assessed. Of all farm machines, efficient diesel tractors have the highest GHG mitigation potential: 12.35 MT of CO₂ equivalent by 2050 and 4.7 MT of CO₂ equivalent by 2030. In addition, GHG abatement cost curves show that biodiesel tractors and efficient diesel tractors have the highest GHG mitigation potential, with attractive abatement costs of -\$62 and -\$11 tonne⁻¹ of CO₂ mitigated by 2050, respectively.*

Keywords. *Abatement cost, Agriculture sector, Energy efficiency, GHG mitigation, LEAP model.*

The world's population is increasing and is expected to reach 9.15 billion by 2050 (Nikos and Jelle, 2012) from 7.3 billion in 2015 (UN, 2015). Agriculture production has increased to meet the growing food demand, and production will need to increase by 60% in 2050 from 2005-2007 values (Nikos and Jelle, 2012). The agriculture sector uses direct (fuels and electricity) and indirect (pesticides and fertilizers) energy. Globally, the agriculture sector emitted 5.07 Pg carbon dioxide equivalent emissions in 2010 (FAOSTAT, 2017). Global agriculture accounts for 52% of anthropogenic methane and 84% of nitrous oxide emissions (Smith et al., 2008), which signifies the importance of reducing emissions from this sector. Canada's agriculture sector is one of the largest producers of flaxseed, canola, pulses, and durum wheat in the world and

emitted 55 MT of CO₂ equivalent in 2011 (ECCC, 2017).

Yield and energy efficiencies have improved considerably in the agriculture sector over the past few decades; however, the emissions profile has not improved (Schneider and Smith, 2009). A few studies have evaluated the GHG emissions mitigation potential in the agriculture sector. Most of the studies investigating reduction of energy-based emissions have focused on indirect energy use, where mitigation potential is evaluated in terms of fertilizers, manure, and water management practices (Smith et al., 2008; Golub et al., 2009; Li et al., 2013; Wang et al., 2014; Nayak et al., 2015). A few studies have conducted qualitative analyses that provide a framework or statistical model for investigating the emissions mitigation potential in the agriculture sector (Lal, 2016; Nayak et al., 2015; Schneider and Smith, 2009). However, there is no comprehensive study on the emissions mitigation potential in the agriculture sector from direct energy consumption through a bottom-up approach because there is little data on end-use energy consumption or energy intensity level. Direct energy consumption in the agriculture sector includes electricity and fossil fuel use in crop cultivation, livestock, and poultry production activities and provide the potential to reduce GHG emissions by adopting new and more efficient technologies.

The Long-range Energy Alternatives Planning (LEAP) model is a tool used for energy planning and for evaluating GHG emissions and the costs incurred in the adoption of GHG mitigation options (SEI, 2011). Final energy demand,

Submitted for review in April 2017 as manuscript number ES 12407; approved for publication by the Energy Systems Community of ASABE in March 2018.

The authors are **Marziyeh Bonyad**, Graduate Student, and **Hafiz Umar Shafique**, Graduate Student, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada; **Md. Alam Hossain Mondal**, Postdoctoral Fellow, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada, and International Food Policy Research Institute, Washington D.C.; **Veena Subramanyam**, Graduate Student, **Amit Kumar**, Professor, and **Md. Ahiduzzaman**, Postdoctoral Fellow, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada; **Corresponding author:** Amit Kumar, Donadeo Innovation Centre for Engineering, 9211 116 Street NW, Edmonton, Alberta, Canada T6G 1H9; phone: 780-492-7797; e-mail: Amit.Kumar@ualberta.ca.

GHG emissions, and GHG mitigation costs in the transportation and electricity generation sectors have been studied using LEAP by several researchers (Kumar et al., 2003; Shabbir and Ahmad, 2010; McPherson and Karney, 2014; Rogan et al., 2014; Subramanyam et al., 2015).

Alberta has the second largest number of farms in Canada. According to the 2006 agricultural census, there were 49,431 farms in the province, covering 52 million acres, which represents 31.2% of Canada's farmland (Statistics Canada, 2009). There is an increasing demand for energy in Alberta's agriculture sector. The sector emitted 2.5 MT of CO₂ in 2009 (NRCan, 2012c). The emissions in the sector emphasize the importance of reducing agricultural energy consumption in Canada's overall GHG mitigation action plan (NRCan, 2012c). In the agriculture sector, energy use is related to agricultural production activities, farm type, and production practices. The complexity of these factors and their relationships require a model that accounts for macroeconomics, supply-demand scenarios, resource use and transformation, and environmental effects.

The overall objective of this study is to assess a variety of energy efficiency options and their associated GHG mitigation potential in the agriculture sector. The specific objectives are to:

- Develop an energy supply-demand model for the agriculture sector.
- Identify energy efficiency scenarios and calculate the cost of saved energy for each scenario.
- Evaluate the GHG mitigation potential and GHG abatement cost (\$ tonne⁻¹) for each scenario in Alberta, Canada.

METHODOLOGY

LEAP MODEL

LEAP, an energy-environmental modeling tool, was developed by the Stockholm Environment Institute (SEI, 2011). LEAP is used for bottom-up energy use and end-use accounting analyses. LEAP uses an extensive integrated database, called the Technology and Environment Database (TED), to provide technical characteristics, costs, and emission factors of various technologies. Models developed using LEAP can be used to analyze energy policies, assess GHG mitigation potential, and assess costs of GHG mitigation (SEI, 2011). In addition, LEAP can analyze and forecast energy end-use over a long period (e.g., 20 to 50 years) (SEI, 2011). LEAP uses a built-in database and input data to simulate user-defined scenarios of energy demand and energy supply. These scenarios can be defined for energy or non-energy sectors and can consider GHG emissions or costs in a particular region. LEAP consists of four modules: (1) the demand module, which represents the end-use energy data and details of the primary and secondary fuels; (2) the transformation module, which is responsible for converting the primary fuel to the secondary fuel; (3) the resource module, which performs the accounting of all the primary and secondary fuels; and (4) the TED module for accounting of the emission factors of the primary and secondary fuels. Figure 1 shows the methodology used to perform the scenario

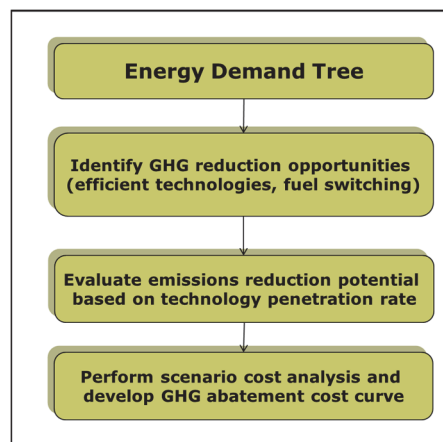


Figure 1. Scenario analysis methodology for Alberta agriculture.

analyses for Alberta's agriculture sector using LEAP. The energy demand tree is developed in the LEAP model, and scenarios are developed based on multiple technology implementation parameters in the agriculture sector.

The demand module for Alberta agriculture consists of the direct energy consumption of farm activities. The module is divided into three sectors: crops, livestock, and "other" (i.e., other farm products and activities). Crops are classified as grain and oilseed, fruit and vegetable, and greenhouse and nursery. Cattle, hogs, poultry and eggs, and dairy are classified under the livestock sector. Alberta agriculture's energy demand is modeled based on the availability of end-use energy data in the province of Alberta and in Canada. Alberta agriculture's demand module is shown in figure 2 (detailed demand modules for each sector are shown in figures A-1 to A-5 and tables A-1 to A-12 in the Appendix). The demand module illustrates the energy demand tree and includes the main sectors and subsectors. Each sector is cascaded into technologies and end-uses. Each subsector is broken down to the end-use level. Each end-use is segregated by various types of primary and secondary fuels. The methodology for providing a descriptive analysis of on-farm energy use is based on an earlier study (Khakbazan, 2000). The data used to formulate the assumptions are listed in table A-13 in the Appendix.

REFERENCE SCENARIO

The reference scenario assumes no mitigation between 2009 and 2050 and considers several macroeconomic factors: production growth rate, population, and GDP. The overall productivity in agriculture between 1940 and 2004 grew at a rate of 1.56% per year (Statistics Canada, 2012; Stewart et al., 2009). In the agriculture model, the annual growth rates for agricultural products are taken from the trends of the past 60 years, i.e., 2.81% growth in crops and other farm products, and 1.84% growth in livestock (Stewart et al., 2009). The growth rates for GDP and population in the agriculture sector are expected to be 3% and 1% per year, respectively, from 2009 to 2050 (NRCan, 2006, 2012c; Statistics Canada, 2012). Table 1 lists the growth rates used in the agriculture model in the reference scenario, and table 2 describes the GHG mitigation scenarios. The electricity generation emissions were estimated based on the policies presented in the Alberta Climate Leadership Plan.

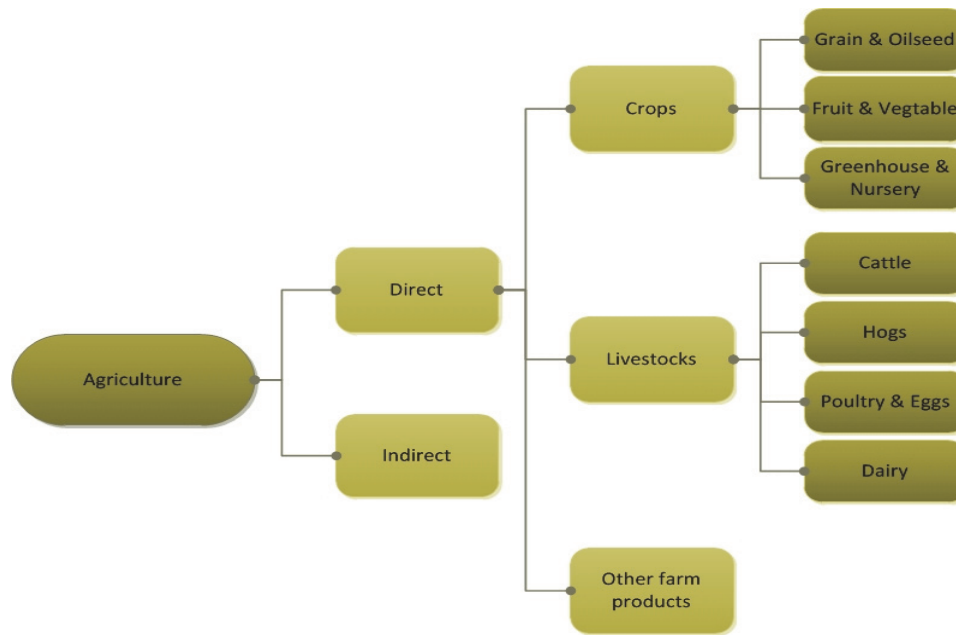


Figure 2. Alberta agriculture's demand module.

Table 1. Growth rates (%) for Alberta's agriculture model reference scenario (2009-2050).^[a]

	2009	2020	2030	2040	2050
Population (million)	3.37	3.8	4.2	4.6	5.1
Agriculture (\$ million Canadian)	3.41	4.7	6.3	8.5	11.5
Agriculture, crops (million tonnes output)	14.85	20.1	26.6	35.1	46.3
Agriculture, livestock (million tonnes output)	3.57	4.40	5.20	6.30	7.50

^[a] Sources: NRCan, 2006; Statistics Canada, 2012; Stewart et al., 2009.

ALTERNATIVE SCENARIOS

In this study, alternative GHG mitigation scenarios were developed for Alberta agriculture's energy demand based on efficiency improvements and the use of renewable energy. The mitigation scenarios were modeled based on two technology penetration rates: slow (2009-2050) and fast (2009-2030). To evaluate the scenarios in terms of overall energy reduction and GHG mitigation, the energy consumption of end-uses, such as farm machinery, irrigation equipment, farm trucks, and livestock and poultry lighting and ventilation, was modeled. The penetration rate was selected for individual scenarios based on the technology maturity status and following an S-curve pattern. The S-curve pattern reflects the technology adoption rate during various phases of the technology's lifetime (Balachandra et al., 2010). Generally, energy-efficient technology adoption has four stages: (1) the idea stage, (2) introduction of the improved technology, (3) increase in acceptance of the improved technology, and (4) mature stage of the improved technology (Packey, 1993). New technologies are adopted slowly at first because the performance of the technology is less known. As time passes and the results from early adopters show promising results, the adoption rate increases exponentially until the market is saturated (Schilling and Esmundo, 2009). In this study, technologies that are mature and tested at a commercial scale are expected to have high penetration, and new technologies are expected to have low penetration during the same period. Penetration rates as low as 5% and as high as 95%, depending on the maturity of the technology, were considered. The penetration rates of each scenario during the

study period are listed in table 2 and discussed in the following sections.

Scenario 1: Poultry Efficient Lighting (PL-CFL)

In this scenario, the mitigation is the replacement of incandescent bulbs by compact fluorescent lamps (CFLs), which are highly energy efficient. Typically, converting from incandescent bulbs to fluorescent lighting reduces energy use by up to 80% and would thus reduce the energy intensity from 275.8 megajoules per tonne (MJ T^{-1}) of poultry produced to 110.3 MJ T^{-1} (Clarke and Ward, 2006b; NRCan, 2017). In both the slow and fast penetration cases of scenario 1, an energy intensity reduction from 275.8 MJ T^{-1} in 2009 to 110.3 MJ T^{-1} by both 2050 and 2030 was considered. The adoption of energy-efficient lighting is high in Alberta. According to the Pembina Institute, in 2014, the adoption rate of CFL lighting in the household sector in Alberta was 65% (Mohareb and Row, 2014). We assumed that a similar trend would appear in the agriculture sector, and therefore we assumed that the efficient lighting adoption rate in all efficient lighting scenarios would reach 90% by the end of the study period (Subramanyam et al., 2013).

Scenario 2: Poultry Efficient Lighting (PL-T8)

In this scenario, the incandescent bulbs are replaced with T8 fluorescent tubes. The efficiency of T8s is expected to be 88%, which has a potential for high energy savings (up to 68%) compared to incandescent bulbs (Clarke and Ward, 2006b; NRCan, 2017). The energy intensity is expected to be reduced from 275.8 MJ T^{-1} in 2009 to 88.3 MJ T^{-1} in both the slow (2050) and fast (2030) penetration cases.

Table 2. Descriptions and penetration rates of GHG mitigation scenarios.

Scenario Number and Name	Scenario Description	Year	Penetration Rate (%)			
			Slow		Fast	
			Existing	New	Existing	New
1 Poultry efficient lighting (PL-CFL)	Existing incandescent bulbs will be replaced by high-efficiency lights, such as compact fluorescent lamps (CFLs), which will result in 40% improvement in energy intensity (Clarke and Ward, 2006b; NRCan, 2017).	2015	90	10	90	10
		2020	80	20	70	30
		2030	50	50	10	90
		2040	25	75	-	-
		2050	10	90	-	-
2 Poultry efficient lighting (PL-T8)	Existing incandescent bulbs with 20% efficiency will be replaced by T8 fluorescent tubes with 88% efficiency (Clarke and Ward, 2006b; NRCan, 2017).	2015	90	10	90	10
		2020	80	20	70	30
		2030	50	50	10	90
		2040	25	75	-	-
		2050	10	90	-	-
3 Dairy and cattle efficient lighting (DCL-T8)	Existing incandescent bulbs with 20% efficiency will be replaced by T8 fluorescent tubes with 88% efficiency (Clarke and Ward, 2006b; NRCan, 2017).	2015	90	10	90	10
		2020	80	20	70	30
		2030	50	50	10	90
		2040	25	75	-	-
		2050	10	90	-	-
4 Swine/hog efficient lighting (SL-T8)	Existing incandescent bulbs with 20% efficiency will be replaced by T8 fluorescent tubes with 88% efficiency (Clarke and Chambers, 2006).	2015	90	10	90	10
		2020	80	20	70	30
		2030	50	50	10	90
		2040	25	75	-	-
		2050	10	90	-	-
5 Dairy, cattle, hog efficient ventilation (DCH-EV)	Current fans in livestock production with 8.4 cfm W ⁻¹ efficiency will be replaced by fans with 18.6 cfm W ⁻¹ efficiency (50% more energy efficient) (Clarke and Ward, 2006a).	2015	95	5	90	10
		2020	90	10	75	25
		2030	75	25	35	65
		2040	50	50	-	-
		2050	35	65	-	-
6 Poultry efficient ventilation (PEV)	Current fans in poultry and egg production with 8.4 cfm W ⁻¹ efficiency will be replaced by fans with 18.6 cfm W ⁻¹ efficiency (50% more energy efficient) (Clarke and Ward, 2006a).	2015	95	5	90	10
		2020	90	10	75	25
		2030	75	25	35	65
		2040	50	50	-	-
		2050	35	65	-	-
7 Efficient diesel tractors (EFF-Trac)	The final energy intensity of tractors is assumed to be reduced by 20% by converting Tier III engines to more efficient Tier IV engines (Yolo County, 2011).	2015	95	0	70	25
		2020	75	20	30	65
		2030	30	65	15	80
		2040	15	80	-	-
		2050	15	80	-	-
8 Biodiesel tractors (Bio-Trac)	The energy intensity of biodiesel tractors is the same as that of diesel tractors. B5 and B20 blends reduce CO ₂ by 20% and reduce other hydrocarbons by 2% to 5% (Subramanyam et al., 2013; USDOE, 2003).	2015	92	3	90	5
		2020	85	10	87	8
		2030	72	23	85	10
		2040	65	30	-	-
		2050	65	30	-	-
9 Biodiesel combines (Bio-Com)	A biodiesel combine has the same energy intensity as a diesel engine combine, and biodiesel combines could mitigate GHGs by 20% (MAFRI, 2012; Statistics Canada, 2012).	2015	92	3	90	5
		2020	85	10	87	8
		2030	72	23	85	10
		2040	65	30	-	-
		2050	65	30	-	-
10 Tankless water heater in dairy (TL-D)	Existing storage tank water heaters in dairy production will be replaced by high-efficiency tankless water heaters, resulting in an energy efficiency improvement of 60% (Sieniewicz, 2012).	2015	90	10	85	15
		2020	80	20	50	50
		2030	25	75	5	95
		2040	5	95	-	-
		2050	5	95	-	-
11 Electrical remote power systems replacing hydraulic systems in tractors (Ele-R)	Existing hydraulic power systems in tractors used in crops will be replaced by high-efficiency electrical remote power systems that will provide better performance, lower heat loss, and diesel fuel savings. Switching will result in an energy intensity improvement of 20% (Papworth, 2014).	2015	93	2	95	5
		2020	90	5	85	15
		2030	70	25	60	35
		2040	60	35	-	-
		2050	60	35	-	-
12 E Electricity efficiency improvement in irrigation systems (IRR-E)	Existing irrigation systems with old and inefficient pumps and motors, along with other equipment in the water line, will be replaced by high-efficiency equipment (including matching equipment and impellers, and periodic maintenance) that will result in energy savings of 36% for electrically powered irrigation systems and 29% for natural gas powered irrigation systems (Dill, 2010).	2015	90	10	85	15
		2020	70	30	50	50
		2030	40	60	20	80
		2040	20	80	-	-
		2050	20	80	-	-
12 NG Natural gas efficiency improvement in irrigation systems (IRR-NG)	Existing irrigation systems with old and inefficient pumps and motors, along with other equipment in the water line, will be replaced by high-efficiency equipment (including matching equipment and impellers, and periodic maintenance) that will result in energy savings of 36% for electrically powered irrigation systems and 29% for natural gas powered irrigation systems (Dill, 2010).	2015	90	10	85	15
		2020	70	30	50	50
		2030	40	60	20	80
		2040	20	80	-	-
		2050	20	80	-	-

Scenario 3: Dairy and Cattle Efficient Lighting (DCL-T8)

This scenario considers the substitution of incandescent bulbs with T8 fluorescent tubes (Clarke and House, 2006),

which are projected to reduce the energy intensity from 40 and 38 MJ T⁻¹ in 2009 to 13 and 12 MJ T⁻¹ in the slow and fast penetration cases, respectively, in the cattle and dairy subsector.

Table 2 (continued). Descriptions and penetration rates of GHG mitigation scenarios.

Scenario Number and Name	Scenario Description	Year	Penetration Rate (%)			
			Slow		Fast	
			Existing	New	Existing	New
13 Energy-efficient waterers in cattle (EF-W)	Existing concrete tank water heaters will be replaced by high-efficiency electric heaters that provide better heating and insulation, resulting in 40% energy intensity savings for feedlots and cow-calf farms (Papworth, 2013).	2015	90	10	85	15
		2020	70	30	50	50
		2030	40	60	20	80
		2050	20	80	-	-
14 Biodiesel trucks (Bi-Tru)	B5 to B20 blends are used as alternative fuels for diesel trucks. The final energy intensity of biodiesel trucks is assumed to be the same as that of diesel trucks; thus, there is no energy savings, but GHGs can be mitigated by up to 20% (Khakbazan, 2000).	2015	93	2	90	5
		2020	90	5	87	8
		2030	87	8	85	10
		2040	85	10	-	-
15 High-efficiency diesel trucks (HEV-Tru)	This scenario proposes replacing diesel trucks with high-efficiency vehicle (HEV) diesel trucks. The final energy intensity improvement from the new engine is expected to be 20% ((Malloy and Lachapelle, 2012; USDOE, 2003).	2015	93	2	90	5
		2020	90	5	87	8
		2030	87	8	85	10
		2040	85	10	-	-
16 Ethanol trucks (E-Tru)	This scenario uses E85-based fuel (85% ethanol) instead of gasoline. The energy intensity of ethanol is the same as that of gasoline (NRCAN, 2012d; USDOE, 2003), and ethanol produces lower GHG emissions.	2015	5	0	5	0
		2020	3	2	3	3
		2030	2	3	0	5
		2040	0	5	-	-
		2050	0	5	-	-

Scenario 4: Swine/Hog Efficient Lighting (SL-T8)

The efficient lighting scenario for Alberta’s hog subsector was set up by replacing incandescent bulbs with T8 fluorescent tubes, which have 88% efficiency (Clarke and Chambers, 2006; NRCAN, 2017).

Scenario 5: Dairy, Cattle, Hog Efficient Ventilation (DCH-EV)

In this scenario, we assumed that current livestock ventilation fans with a capacity of 8.4 cubic feet of air per minute per watt (cfm W⁻¹) are replaced by 18.6 cfm W⁻¹ fans with 50% more energy efficiency (Clarke and Ward, 2006a; Jacobson and Chastain, 1994). A medium penetration rate was assumed for the new efficient fans based on an earlier study (Navigant, 2009; Subramanyam et al., 2013).

Scenario 6: Poultry Efficient Ventilation (P-EV)

In this scenario, we assumed that existing ventilation fans, with a capacity of 8.4 cfm W⁻¹, are replaced by fans with a capacity 18.6 cfm W⁻¹. The final energy intensity in this mitigation scenario is expected to decline to 50% by 2050 when existing fans are replaced by high-efficiency fans (Clarke and Ward, 2006a; Jacobson and Chastain, 1994). The penetration rate of efficient fans is considered to reach a medium level of 65% by the end of both 2050 and 2030. This assessment of the penetration rate was based on an earlier study (Navigant, 2009; Subramanyam et al., 2013).

Scenario 7: Efficient Diesel Tractors (EFF-Trac)

The efficient diesel tractors scenario was developed based on an earlier study (Yolo County, 2011). According to that study, 15% to 20% of the energy was saved by converting old tractor engines to Tier IV engines. In this scenario, the final energy intensity of tractors was assumed to be reduced by 20% by converting Tier III engines to more efficient Tier IV engines.

Scenario 8: Biodiesel Tractors (Bio-Trac)

One way to mitigate the GHGs emitted by farm machinery is to replace diesel fuel with biodiesel, a “clean” fuel. The biodiesel tractors scenario considers blends of B5 to

B20. In this scenario, the energy intensity of biodiesel tractors was assumed to be the same as that of diesel tractors. By using B5 and B20, a 20% reduction of CO₂ and a 2% to 5% reduction of CO and other hydrocarbon emissions is anticipated (Subramanyam et al., 2013; USDOE, 2003). The slow and fast penetration cases were developed in LEAP, and a penetration rate of 30% is achieved by the end of both 2050 and 2030 (Khakbazan, 2000).

Scenario 9: Biodiesel Combines (Bio-Com)

In Canada’s agriculture sector, combines account for 20% of the energy used in grain and oilseed farm machinery. This number was estimated using tractor and combine specifications and farm machinery population data (MAFRI, 2012; Statistics Canada, 2012). We assumed that replacing combine diesel fuel with biodiesel could reduce CO₂ emissions by 20% (Subramanyam et al., 2013). In the biodiesel combines scenario, biodiesel was proposed as an alternative fuel to reduce GHG emissions. However, as in the biodiesel tractors scenario, the penetration rate of biodiesel (B5 to B20) combines is expected to be low and reach the maximum level of 30% by the end of slow and fast penetration (Khakbazan, 2000).

Scenario 10: Tankless Water Heaters in Dairy (TL-D)

Tankless water heaters, also referred to as on-demand or instantaneous water heaters, have either an electric element or a gas burner that provides the required amount of heat to flowing water, thus eliminating the need for a storage tank. The water is heated only when required, thereby reducing any losses associated with storing heated water. Tankless water heaters can result in savings of 60% in a dairy operation and require less energy, e.g., 109.8 MJ T⁻¹ as compared to 274.9 MJ T⁻¹ for existing water heaters (Sieniewicz, 2012). The penetration rate of tankless water heaters in the dairy subsector is assumed to be high; 95% penetration of this technology is assumed by the end of the study period. These penetration rates are similar to those of earlier studies (Navigant, 2009; Subramanyam et al., 2013).

Scenario 11: Electrical Remote Power Systems Replacing Hydraulic Systems in Tractors (Ele-R)

The tractors used in the crop sector use hydraulic remote power systems that incur high energy losses due to inherent inefficiencies and heat losses in the system. Due to the large equipment size in the crop sector and the growth in the agriculture sector, hydraulic systems are becoming larger, and in turn their energy demand is increasing significantly. Manufacturers are replacing hydraulic systems with electrical systems that would lower the diesel energy requirement in crop operations by 20% (Papworth, 2014). Based on previous studies (Navigant, 2009; Subramanyam et al., 2013), the penetration rate for electrical remote systems is expected to approach 35% by the end of the study period.

Scenario 12: Electricity and Natural Gas Energy Efficiency Improvement in Irrigation Systems (IRR-E, IRR-NG)

A significant portion of the energy demand in the crop sector is for irrigation systems, which use either natural gas or electricity for the wheel line and section pivots. According to an earlier study, efficiency improvement in irrigation systems can result in savings of 29% in natural gas-based irrigation systems and 36% in electricity-based systems (Dill, 2010). The penetration rate of high-efficiency equipment is expected to be high (80%) by the end of both the slow and fast penetration cases (Navigant, 2009; Subramanyam et al., 2013).

Scenario 13: Energy-Efficient Waterers in Cattle (EF-W)

In the cattle subsector, a large amount of electricity is consumed to heat water for livestock during cold periods. Currently, beef feedlots typically use concrete waterers because they are durable. However, there is a large potential to improve efficiency by using energy-efficient waterers that have more insulation, smaller heating elements, and accurate thermostats. Based on an earlier study, it is estimated that energy-efficient waterers in the cattle subsector can result in energy savings of 40% compared to existing waterers (Papworth, 2013). Based on previous studies (Navigant, 2009; Subramanyam et al., 2013), by the end of the study period, the penetration rate of efficient waterers is expected to increase to 80%.

Scenario 14: Biodiesel Trucks (Bio-Tru)

This scenario considers the use of biodiesel with blends of B5 to B20 as an alternative fuel for diesel trucks. The penetration rate was considered to be low to medium, as reported in the World Energy Council's report on global penetration rates of biofuel vehicles (WEC, 2011). Based on this assumption, both penetration cases in the LEAP model are expected to reach a maximum penetration rate of 10% by the end of the study period. The final energy intensity of biodiesel trucks is considered to be the same as that of diesel trucks.

Scenario 15: High-Efficiency Diesel Trucks (HEV-Tru)

High-efficiency diesel engines can affect fuel consumption and GHG mitigation. Modern diesel engines use electronically controlled fuel injection, which increases energy

efficiency (Malloy and Lachapelle, 2012; USDOE, 2003). In the LEAP model, the final energy intensity improvement from using the new engines is assumed to be 20%. The penetration rate for high-efficiency vehicle (HEV) diesel trucks is categorized as medium. It is difficult for fuel-saving technology to penetrate the new truck market, although high-efficiency diesel engines can significantly reduce fuel consumption (EIA, 1999). With this constraint and based on the S-curve pattern (Balachandra et al., 2010), the low penetration rate of HEV diesel trucks was selected in the LEAP model. We assumed that up to 10% of existing diesel trucks will be converted to HEV diesel trucks by 2050 and 2030.

Scenario 16: Ethanol Trucks (E-Tru)

Ethanol-blended gasoline is a renewable fuel, and unleaded gasoline contains up to 10% ethanol. This scenario assumes the use of E85-based fuel (i.e., 85% ethanol) instead of gasoline in trucks. E85-based fuel is compatible with special engines only; thus, existing gasoline engines will have to be replaced. The energy intensity of E85 in farm trucks is assumed to be the same as that of gasoline (NRCAN, 2012b, 2012d; USDOE, 2013). This energy intensity refers to the energy required from biofuel or ethanol per unit of entity transported in a period of time for a particular end-use and vehicle type. This is different from the calorific value of the fuel. However, the advantage of using ethanol rather than gasoline is the lower GHG emissions (NRCAN, 2012a). In the LEAP model, both penetration cases were developed based on a low penetration rate. In the slow and fast penetration cases, full replacement of pure gasoline trucks with E85-based trucks is achieved by the end of 2050 and 2030, based on earlier studies (Subramanyam et al., 2013; WEC, 2011).

COSTS OF GHG MITIGATION SCENARIOS

The costs incurred by the proposed energy-efficiency scenarios were evaluated with the LEAP model. The cost-benefit analysis in the LEAP model includes an estimate of the cost of saved energy (CSE) (Kong et al., 2015). The CSE values for estimating the techno-economic cost of implementing each scenario are expressed as dollars per gigajoule ($\$ \text{GJ}^{-1}$) depending on the model characteristics (Billingsley et al., 2014; Friedrick et al., 2009; Meier, 1982). The CSE values were calculated based on the investment cost, saved energy from the new technology, annual cost savings from saved energy, lifetime of the technology, and interest rate, as shown in equation 1 and table 3. All monetary values used in the CSE calculations are real dollars and are therefore adjusted for inflation. Investment costs were assumed to stay constant in real terms, and a 5% interest rate was applied for the capital recovery factor (CRF). The CSE value for each scenario was input into the model. The cost of mitigation output from the model resulted from the CSE, saved energy, and GHG mitigation for each scenario. A 5% discount rate was then applied to the projected cost results to arrive at a net present value (NPV) in 2017 dollars:

$$\text{CSE} = (I \times \text{CRF} - D \times P) / D \quad (1)$$

where

I = investment cost of new technology

D = annual saved energy

Table 3. Techno-economic input data for GHG mitigation cost analysis.

Scenario	Unit ^[a]	Cost of Saved Energy (CSE) Average				References for Assumptions in CSE Calculations ^[b]
		2010-2020	2020-2030	2030-2040	2040-2050	
1	\$ kWh ⁻¹	-0.11	-0.16	-0.21	-0.29	Clarke and Ward, 2006b
2	\$ kWh ⁻¹	-0.01	-0.06	-0.11	-0.19	Clarke and Ward, 2006b
3	\$ kWh ⁻¹	-0.09	-0.13	-0.19	-0.27	Clarke and House, 2006
4	\$ kWh ⁻¹	-0.09	-0.13	-0.19	-0.27	Clarke and Chambers, 2006
5	\$ kWh ⁻¹	-0.51	-0.73	-1.01	-1.40	Clarke and Ward, 2006a; Sundby, 2013
6	\$ kWh ⁻¹	-1.03	-1.48	-2.03	-2.81	Clarke and Ward, 2006a; Sundby, 2013
7	\$ GJ ⁻¹	-3.11	-1.41	-2.30	-2.82	Yolo County, 2011
8	\$ tonne ⁻¹	2.20	0.98	-1.63	-4.24	Yolo County, 2011; USDOE, 2008
9	\$ tonne ⁻¹	0.30	0.13	-0.22	-0.59	MAFRI, 2012
10	\$ GJ ⁻¹	-8.33	-9.44	-10.55	-12.21	A. O. Smith, 2012
11	\$ GJ ⁻¹	-28.86	-31.54	-33.22	-35.00	Yolo County, 2011
12 E	\$ kWh ⁻¹	-0.08	-0.12	-0.18	-0.26	Dill, 2010
12 NG	\$ GJ ⁻¹	1.07	1.04	1.01	1.00	Dill, 2010
13	\$ kWh ⁻¹	-0.12	-0.17	-0.22	-0.30	Papworth, 2013
14	\$ km ⁻¹	0.10	0.04	-0.07	-0.19	CALSTART, 2010
15	\$ GJ ⁻¹	-4.44	-4.44	-5.55	-5.55	CALSTART, 2010
16	\$ km ⁻¹	0.12	0.06	-0.07	-0.2	CALSTART, 2010
Fuel type		Fuel price considered in calculation				
Electricity	\$ kWh ⁻¹	0.12	0.17	0.22	0.30	NEB, 2011
Diesel	\$ GJ ⁻¹	32.19	33.80	35.49	37.30	NEB, 2011
Gasoline	\$ GJ ⁻¹	42.18	44.4	46.62	48.95	NEB, 2011
Natural gas	\$ GJ ⁻¹	8.33	9.44	10.55	12.21	NEB, 2011
Biodiesel	\$ GJ ⁻¹	35.09	35.09	33.33	21.64	USDOE, 2011
Ethanol	\$ GJ ⁻¹	46.40	46.40	44.07	41.85	USDOE, 2011, 2013

^[a] Based on 2017 Canadian dollars.

^[b] Includes capital cost, fuel cost, operation and maintenance cost, and operating life of the technology.

P = unit price of energy

$$CRF = (i \times (1 + i)^n) / [(1 + i)^n - 1]$$

i = interest rate (5%)

n = year.

Table A-13 in the Appendix contains detailed assumptions for the cost of each scenario. A sensitivity analysis was conducted for the 2009-2050 period using the inputs (CSE, discount rate, reference scenario growth rate, and alternate scenario energy intensity improvements) to evaluate impacts on the cost (\$ tonne⁻¹) of mitigation and total GHG mitigation. The results of the sensitivity analysis are provided in figures A-6 to A-39 in the Appendix.

RESULTS AND DISCUSSION

ENERGY DEMAND FOR BASE YEAR

The energy demand for Alberta agriculture was calculated for the base year 2009 using a bottom-up energy demand tree in LEAP that allows detailed tracking of energy consumption by fuel type (table 4). Diesel fuel is the most widely used energy source in agriculture, followed by gasoline and natural gas. Diesel and gasoline, as the most GHG-

intensive fuels in the sector, present opportunities for GHG mitigation through improving efficiency by using low-GHG energy sources such as natural gas or electricity.

GHG EMISSIONS FOR BASE YEAR

Table 5 lists the overall GHG emissions in agriculture from various types of energy for the base year 2009. Live-stock is the most GHG-intensive sector in Alberta agriculture.

ENERGY DEMAND FOR REFERENCE SCENARIO

Growth in the energy demand of Alberta agriculture is expected to increase from 41.6 to 106 PJ over the 42-year period from 2009 to 2050, as shown in table 6. Consequently, it is expected that consumption of all types of energy will increase during this period. More precisely, the consumption of diesel, the most widely used fuel in agriculture, is expected to increase from 23.4 PJ in 2009 to 59.3 PJ in 2050. Motor gasoline consumption is expected to increase from 6.89 PJ in 2009 to 17.37 PJ in 2050, while the consumption of electricity and NG will increase from 5.9 and 6.14 PJ to 15.27 and 15.9 PJ, respectively.

Table 4. Alberta agriculture's energy demand by fuel type (TJ).^[a]

Sector and Subsector	Diesel	Electricity	Gasoline	LPG	Natural Gas
Crops	9,811	1,512	885	66	1,620
Grain and oilseed	9,627	1,255	774	56	1,340
Fruit and vegetable	101	34	20	2	30
Greenhouse and nursery	83	223	90	8	250
Livestock	14,923	3,114	2,213	131	3,226
Cattle	12,811	2,028	1,862	90	2,147
Hog	742	320	129	11	343
Poultry and eggs	251	443	68	15	445
Dairy	1,118	322	153	16	291
Other	973	1,281	531	56	1,298
Total	25,707	5,906	3,629	253	6,145

^[a] Sources: NRCan, 2006; Statistics Canada, 2012.

Table 5. Overall GHG emissions (MT CO₂ eq.) for different sectors of Alberta agricultural for various fuel types in 2009.^[a]

Sector and Subsector	Diesel	Gasoline	LPG	Natural Gas	Electricity
Crops	0.73	0.06	0.00	0.09	0.46
Grain and oilseed	0.71	0.06	0.00	0.07	0.38
Fruit and vegetable	0.01	0.00	0.00	0.00	0.01
Greenhouse and nursery	0.01	0.00	0.00	0.01	0.07
Livestock	1.11	0.16	0.01	0.18	0.95
Cattle	0.95	0.13	0.01	0.12	0.62
Hog	0.06	0.01	0.00	0.02	0.10
Poultry and eggs	0.02	0.01	0.00	0.02	0.14
Dairy	0.08	0.01	0.00	0.02	0.10
Other	0.07	0.04	0.00	0.07	0.39
Total	1.90	0.26	0.02	0.34	1.80

^[a] Sources: NRCan, 2006; Statistics Canada, 2012.

Table 6. Energy demand growth (PJ) in Alberta agriculture as estimated by the LEAP model.

Sector and Subsector	2009	2020	2030	2040	2050
Crops	13.894	18.846	24.864	32.804	43.279
Grain and oilseed	13.052	17.704	23.357	30.816	40.656
Fruit and vegetable	0.187	0.254	0.335	0.442	0.584
Greenhouse and nursery	0.655	0.888	1.172	1.546	2.04
Livestock	23.607	28.85	34.62	41.544	49.853
Cattle	18.938	23.144	27.773	33.328	39.994
Hog	1.546	1.889	2.267	2.72	3.264
Poultry and eggs	1.222	1.494	1.793	2.151	2.581
Dairy	1.901	2.323	2.787	3.345	4.014
Other	4.14	5.615	7.408	9.774	12.895
Total	41.641	53.311	66.892	84.122	106.027

GHG EMISSIONS FOR REFERENCE SCENARIO

The GHG emissions of Alberta agriculture based on direct energy use are expected to increase from 2.58 MT of CO₂ in 2009 to 6.4 MT of CO₂ equivalent in 2050 in the reference scenario. Factoring in the upstream electricity emissions, the total emissions are expected to increase from 4.33 MT of CO₂ in 2009 to 7.81 MT of CO₂ equivalent in 2050. The emissions contributions for each agriculture sector are listed in table 7.

GHG MITIGATION FOR ALTERNATIVE SCENARIOS

Table 8 summarizes the cost and GHG mitigation results for each scenario. Figures 3 and 4 show the GHG abatement cost curves to illustrate the relative cost and GHG mitigation potential of each scenario in the two penetration periods (2009-2050 and 2009-2030, respectively). A detailed analysis of each scenario is provided in the following sections.

Table 7. GHG emissions (MT CO₂ eq.) in the reference scenario for Alberta agriculture as estimated by the LEAP model.

Emission Type	Sector	2009	2020	2030	2040	2050
Direct (excludes electricity emissions)	Crops	0.89	1.20	1.59	2.09	2.76
	Livestock	1.45	1.78	2.13	2.56	3.07
	Other	0.19	0.25	0.33	0.44	0.58
	Total	2.53	3.23	4.05	5.09	6.41
Direct and indirect	Crops	1.35	1.62	1.83	2.42	3.19
	Livestock	2.4	2.55	1.54	3.06	3.67
	Other	0.58	0.61	0.54	0.72	0.95
	Total	4.33	4.78	4.91	6.19	7.81

Table 8. Summary of results for GHG mitigation scenarios as developed by LEAP model.^[a]

Scenario Number and Name	Fast Growth Market by 2030			Slow Growth Market by 2050		
	Net GHG Mitigated (MT)	NPV of Cost (million \$)	Cost of Mitigation (\$ T ⁻¹)	Net GHG Mitigated (MT)	NPV of Cost (million \$)	Cost of Mitigation (\$ T ⁻¹)
1 Poultry efficient lighting (PL-CFL)	0.03	-5.2	-180	0.06	-13.2	-215
2 Poultry efficient lighting (PL-T8)	0.03	-2	-62	0.07	-8.0	-116
3 Dairy and cattle efficient lighting (DCL-T8)	0.15	-23.1	-154	0.32	-61.3	-193
4 Swine/hog efficient lighting (SL-T8)	0.06	-8.7	-154	0.12	-23.0	-193
5 Dairy, cattle, hog efficient ventilation (DCH-EV)	0.49	-411.9	-834	0.82	-850.7	-1037
6 Poultry efficient ventilation (PEV)	0.02	-25.7	-1681	0.03	-53.0	-2084
7 Efficient diesel tractors (EFF-Trac)	4.70	-23.1	-5	12.35	-130.7	-11
8 Biodiesel tractors (Bio-Trac)	0.62	1031	1676	4.81	-297.6	-62
9 Biodiesel combines (Bio-Com)	0.06	139.5	2479	0.47	-43.8	-94
10 Tankless water heaters in dairy (TL-D)	0.08	-9.2	-114	0.24	-17.7	-73
11 Electrical remote power systems in tractors (Ele-R)	0.51	-143.3	-281	2.12	-338.1	-160
12 E Efficiency improvement in irrigation systems (IRR-E)	0.16	-18.8	-121	0.06	-11.1	-181
12 NG Efficiency improvement in irrigation systems (IRR-NG)	0.18	2.6	15	0.09	0.6	7
13 Energy-efficient waterers in cattle (EF-W)	0.62	-101	-162	0.98	-218.3	-224
14 Biodiesel trucks (Bio-Tru)	0.08	49.8	611	0.22	-5.9	-27
15 High-efficiency diesel trucks (HEV-Tru)	0.08	-3.7	-45	0.22	-6.2	-28
16 Ethanol trucks (E-Tru)	0.03	64.1	1941	0.13	6.3	50

^[a] Based on 2017 Canadian dollars; NPV = net present value.

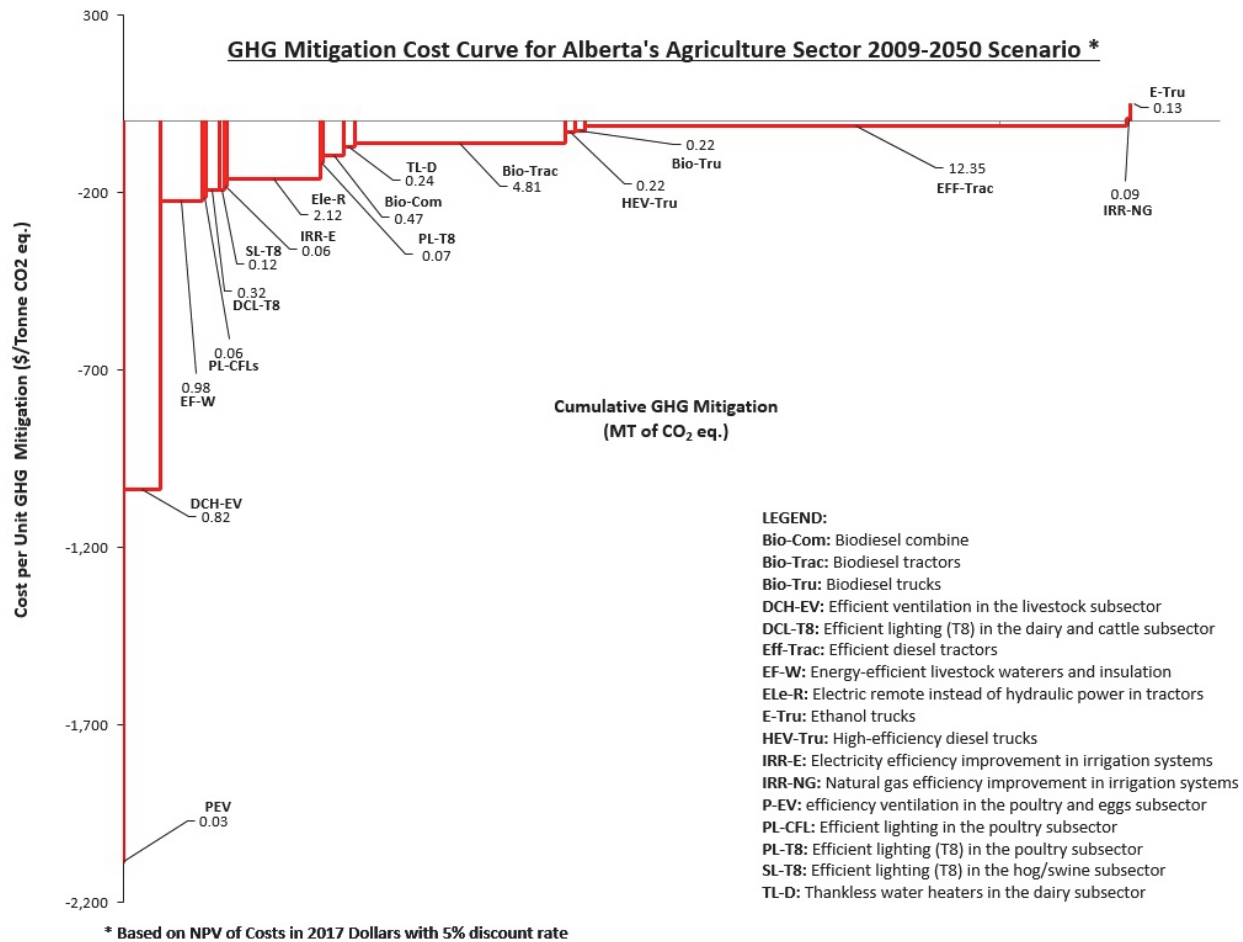


Figure 3. Cost curves for slow penetration (2009-2050) of GHG mitigation scenarios in Alberta agriculture.

Scenario 1: Poultry Efficient Lighting (PL-CFL)

For slow penetration (2050) of scenario 1, a 0.56 PJ electricity demand reduction is estimated by the LEAP model, which is equivalent to an average savings of 0.01 PJ year⁻¹ in electricity. It is estimated that an average mitigation of 0.0015 MT of CO₂ eq. per year can be achieved in this case. For fast penetration (2030) of scenario 1, electricity is reduced by 0.16 PJ by 2030. This is equal to 0.004 PJ year⁻¹ on average. The GHG mitigation is estimated to be 0.0007 MT of CO₂ eq. per year on average. The average GHG mitigation per year is higher with slow penetration because the changes are implemented over a longer period (40 years vs. 20 years). The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Net emission reductions for fast (2030) and slow (2050) penetration of scenario 1 are 0.06 and 0.03 MT of CO₂ eq., respectively, with discounted incremental costs of -\$13.2 million and -\$5.2 million, respectively. Accordingly, the costs per unit of GHG mitigation are -180 and -215 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 2: Poultry Efficient Lighting (PL-T8)

For slow penetration (2050) of scenario 2, the LEAP model calculated an average reduction of 0.02 PJ year⁻¹ in electricity demand during the study period (2010-2050), which is equal to 0.64 PJ of electricity savings by 2050. It is

estimated that an average mitigation of 0.0017 MT of CO₂ eq. per year can be achieved in this scenario during the study period. For fast penetration (2030) of scenario 2, the total reduction of electricity is 0.19 PJ during the study period (2010-2030), with the annual average reduction in GHG emissions estimated to be 0.0008 MT of CO₂ eq. by 2030. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total mitigation for fast and slow penetration is 0.03 and 0.07 MT of CO₂ eq., respectively, with discounted incremental costs of -\$2 million and -\$8 million, respectively. Accordingly, the costs per unit of GHG mitigation are -62 and -116 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 3: Dairy and Cattle Efficient Lighting (DCL-T8)

For slow penetration (2050) of scenario 3, the model estimates a total reduction of 3 PJ in electricity demand during the study period (2010-2050). It is estimated that an average annual mitigation of 0.0078 MT of CO₂ eq. can be achieved in this scenario during the study period. For fast penetration (2030) of scenario 3, total electricity reduction is estimated to be 0.91 PJ, and the annual average GHG emissions reduction is calculated to be 0.0037 MT of CO₂ eq. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total

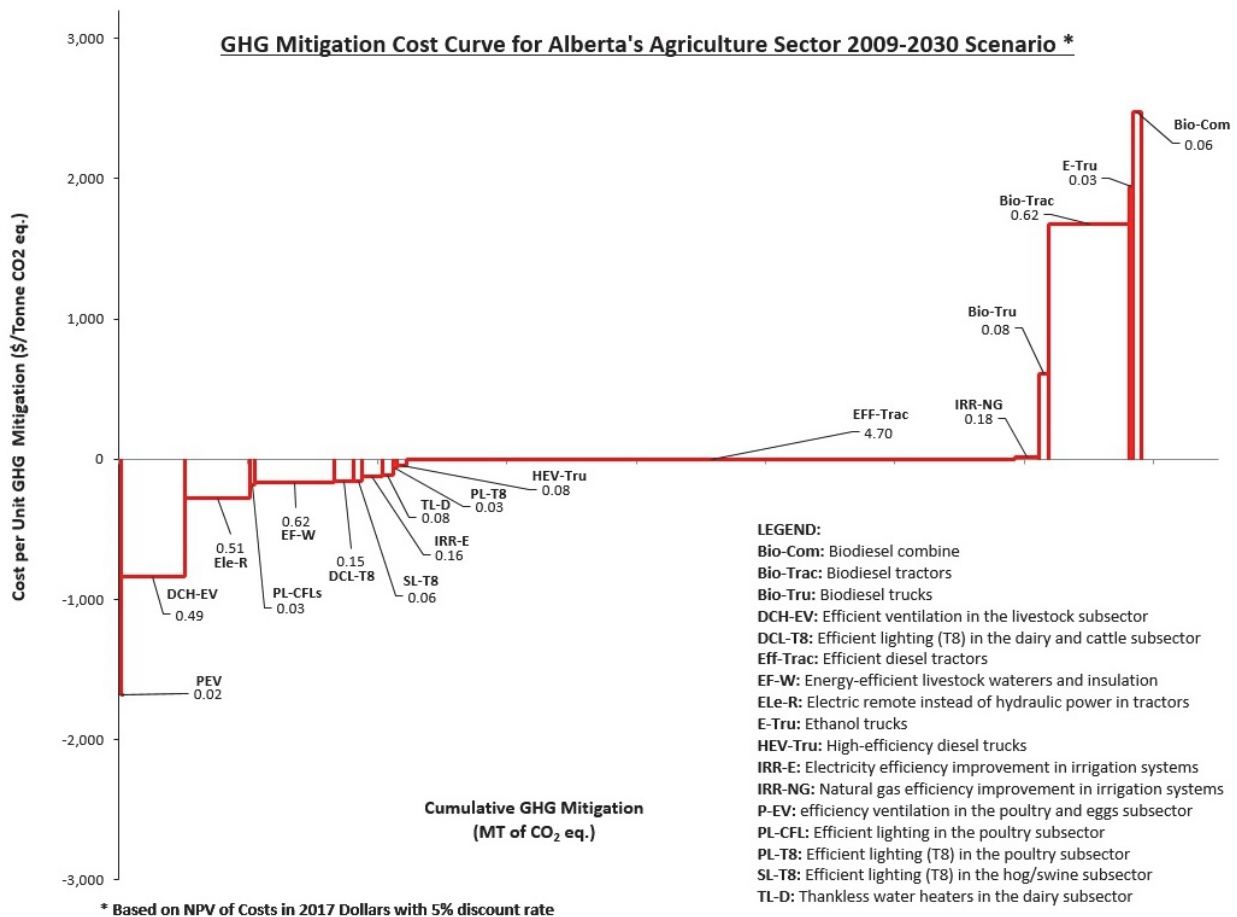


Figure 4. Cost curves for fast penetration (2009-2030) of GHG mitigation scenarios in Alberta agriculture.

emission reductions for fast and slow penetration are 0.15 and 0.32 MT of CO₂ eq., respectively, with discounted incremental costs of -\$23.1 and -61.3 million, respectively. Accordingly, the costs per unit of GHG mitigation are -154 and -193 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 4: Swine/Hog Efficient Lighting (SL-T8)

For slow penetration (2050) of scenario 4, the LEAP model estimates a total reduction of 1.1 PJ in electricity demand during the study period (2010-2050). It is estimated that an annual average mitigation of 0.0029 MT of CO₂ eq. can be achieved in this scenario. For fast penetration (2030) of scenario 4, total electricity reduction is 0.32 PJ, and the annual average GHG emissions reduction is calculated to be 0.0014 MT of CO₂ eq. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.057 and 0.12 MT of CO₂, respectively, with discounted incremental costs of -\$8.7 million and -\$23 million, respectively. Accordingly, the costs per unit of GHG mitigation are -154 and -193 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 5: Dairy, Cattle, Hog Efficient Ventilation (DCH-EV)

For slow penetration (2050) of scenario 5, the LEAP

model calculated a total reduction of 8.02 PJ in electricity demand during the study period (2010-2050), which is equal to an average electricity reduction of 0.20 PJ year⁻¹. An average annual reduction of 0.02 MT of CO₂ eq. is estimated. For fast penetration (2030) of scenario 5, the average electricity reduction is estimated to be 0.076 PJ year⁻¹, and the average GHG emission reduction is calculated to be 0.012 MT of CO₂ eq. per year. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.49 and 0.82 MT of CO₂, respectively, with discounted incremental costs of -\$412 million and -\$851 million, respectively. Accordingly, the costs per unit of GHG mitigation are -834 and -1,037 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 6: Poultry Efficient Ventilation (P-EV)

For slow penetration (2050) of scenario 6, the LEAP model estimates an average reduction of 0.001 PJ year⁻¹ of electricity demand during the study period (2010-2050). It is estimated that an average mitigation of 0.0006 MT of CO₂ eq. per year during the study period can be achieved in this scenario. For fast penetration (2030) of scenario 6, total electricity reduction is estimated to be 0.002 PJ year⁻¹, and the average GHG emissions reduction is calculated to be 0.0004 MT of CO₂ eq. per year by 2030. The incremental NPV of costs and net achievable GHG mitigation estimated by the

LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.015 and 0.025 MT of CO₂ eq., respectively, with discounted incremental costs of -\$26 million and -\$53 million, respectively. Accordingly, the costs per unit of GHG mitigation are -1,681 and -2,084 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 7: Efficient Diesel Tractors (EFF-Trac)

For slow penetration (2050) of scenario 7, the LEAP model estimates an average reduction of 4.16 PJ year⁻¹ in diesel demand during the study period (2010-2050). It is estimated that an average mitigation of 0.3 MT of CO₂ eq. per year during the study period can be achieved in this scenario. For fast penetration (2030) of scenario 7, total diesel reduction is 1.58 PJ year⁻¹ by 2030 (2010-2030), and the net GHG emission reduction is calculated to be 0.115 MT of CO₂ eq. per year. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 4.7 and 12.35 MT of CO₂ eq., respectively, with discounted costs of -\$23 million and -\$131 million, respectively. Accordingly, the costs per unit of GHG mitigation are -5 and -11 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 8: Biodiesel Tractors (Bio-Trac)

For slow penetration (2050) of scenario 8, LEAP estimates a reduction in diesel demand of 5% to 20% per liter of biodiesel blend (B5 to B20), which is equal to the amount of biodiesel added to the blend. However, the total energy demand in this scenario remains the same as the reference scenario. It is estimated that an average mitigation of 0.12 MT of CO₂ eq. per year can be achieved in this scenario. For fast penetration (2030) of scenario 8, there is no change in energy demand, as was found in the slow penetration of this scenario; however, the average GHG mitigation is estimated to be 0.015 MT of CO₂ eq. per year. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.62 and 4.81 MT of CO₂ eq., respectively, with discounted incremental costs of \$1,031 million and \$298 million, respectively. Accordingly, the costs per unit of GHG mitigation are 1,676 and -62 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 9: Biodiesel Combines (Bio-Com)

For slow penetration (2050) of scenario 9, no changes in energy demand are expected. The reduction in diesel demand is about 5% to 20% per liter of biodiesel (B5 to B20) and is equal to the amount of biodiesel added to the blend; thus, the net energy demand remains the same. It is estimated that GHG emissions are reduced by 0.01 MT of CO₂ eq. per year on average during the study period in this scenario. For fast penetration (2030) of scenario 9, the average GHG emissions reduction is calculated to be 0.0014 MT of CO₂ eq. per year. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.06 and 0.47 MT of CO₂ eq., respectively, with discounted

incremental costs of \$140 million and -\$44 million, respectively. Accordingly, the costs per unit of GHG mitigation are 2,479 and -94 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 10: Tankless Water Heaters in Dairy (TL-D)

For slow penetration (2050) of scenario 10, a reduction of 4.3 PJ is estimated by the LEAP model in natural gas demand when tankless hot water heaters are used in the dairy subsector, which is equivalent to an average savings of 0.11 PJ year⁻¹ in natural gas. It is estimated that an average mitigation of 0.006 MT of CO₂ eq. per year can be achieved in this scenario. For fast penetration (2030) of scenario 10, natural gas is reduced by 1.4 PJ by 2030. This is equal to 0.035 PJ year⁻¹ on average. The average GHG mitigation is estimated to be 0.002 MT of CO₂ eq. per year. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions reductions for fast and slow penetration are 0.08 and 0.24 MT of CO₂, respectively, with discounted incremental costs of -\$9.2 million and -17.7 million, respectively. Accordingly, the costs per unit of GHG mitigation are -114 and -73 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 11: Electrical Remote Power Systems Replacing Hydraulic Systems in Tractors (Ele-R)

According to LEAP's estimates for slow penetration (2050) for scenario 11, demand for diesel can be reduced by 28.5 PJ, which is equivalent to an average savings of 0.71 PJ year⁻¹ in diesel demand. It is estimated that an average mitigation of 0.05 MT of CO₂ eq. per year can be achieved in this scenario. For fast penetration (2030) of scenario 11, diesel fuel demand is reduced by 8.2 PJ by 2030. This is equal to 0.205 PJ year⁻¹ on average, and the GHG mitigation is estimated to be 0.01 MT of CO₂ eq. per year on average. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Emission reductions for fast and slow penetration are 0.51 and 2.12 MT of CO₂ eq., respectively, with discounted incremental savings of -\$143 million and -\$338 million, respectively. Accordingly, the costs per unit of GHG mitigation are -281 and -160 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 12: Electricity and Natural Gas Energy Efficiency Improvement in Irrigation Systems (IRR-E, IRR-NG)

In the efficient irrigation system based on the use of natural gas, a net energy reduction of 1.6 PJ is estimated by the LEAP model (an average savings of 0.04 PJ year⁻¹ in natural gas) by the end of the study period (2050). It is estimated that an average mitigation of 0.002 MT of CO₂ eq. per year can be achieved in this scenario. In the efficient irrigation system based on the use of electricity, the LEAP model estimates a reduction of 0.57 PJ in electricity demand by 2050, or an average savings of 0.01 PJ year⁻¹. It is estimated that an average mitigation of 0.0015 MT of CO₂ eq. per year can be achieved in this scenario. In the case of fast penetration, natural gas demand is reduced by 3.1 PJ by 2030. This is

equal to 0.077 PJ year⁻¹ on average. The GHG mitigation is estimated to be 0.004 MT of CO₂ eq. per year on average. Electricity demand in the case of fast penetration is reduced by 0.81 PJ by 2030. This is equivalent to 0.020 PJ year⁻¹ on average. GHG mitigation is estimated to be 0.004 MT of CO₂ eq. per year on average. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emission reductions for fast penetration are 0.176 and 0.156 MT of CO₂ eq., respectively, with a discounted incremental cost and savings of \$2.6 million and -\$18.8 million for natural gas and electricity systems, respectively. Accordingly, the costs per unit of GHG mitigation are 15 and -121 (\$ tonne⁻¹ of CO₂ eq.) for natural gas and electricity systems, respectively, for fast penetration. Total emission reductions for slow penetration are 0.09 and 0.06 MT of CO₂ eq., respectively, with a discounted incremental cost and savings of \$0.6 million and -\$11.1 million for natural gas and electricity systems, respectively. Accordingly, the costs per unit of GHG mitigation are 7 and -181 (\$ tonne⁻¹ of CO₂ eq.) for natural gas and electricity systems, respectively, for slow penetration.

Scenario 13: Energy-Efficient Waterers in Cattle (EF-W)

For slow penetration (2050) of scenario 13, a reduction of 8.9 PJ in electricity demand is estimated by the LEAP model by 2050 through the integration of efficient waterers in the cattle subsector. This saving is equivalent to an average of 0.22 PJ year⁻¹ of electricity. It is estimated that an average mitigation of 0.024 MT of CO₂ eq. per year can be achieved in this scenario. For fast penetration (2030) of scenario 13, electricity use is reduced by 3 PJ by 2030. This is about 0.075 PJ year⁻¹ on average. The GHG mitigation is estimated to be 0.015 MT of CO₂ eq. per year on average. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emission reductions for fast and slow penetration are 0.62 and 0.98 MT of CO₂ eq., respectively, with discounted incremental savings of -\$101 million and -218 million, respectively. Accordingly, the results for cost per unit of GHG mitigation are -162 and -224 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 14: Biodiesel Trucks (Bio-Tru)

Slow penetration (2050) of scenario 14 does not result in any reduction in energy demand. Average emissions are estimated to be reduced by 0.005 MT of CO₂ eq. per year during the study period (2010-2050). For fast penetration (2030) of scenario 14, the average reduction in emissions is estimated to be 0.002 MT of CO₂ eq. per year for the period of 2010 to 2030. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.081 and 0.22 MT of CO₂ eq., respectively, with discounted incremental costs of \$49.8 million and -\$5.9 million, respectively. Accordingly, the costs per unit of GHG mitigation are 611 and -27 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 15: High-Efficiency Diesel Trucks (HEV-Tru)

For slow penetration (2050) of scenario 15, the LEAP model estimates an average reduction of 0.08 PJ year⁻¹ in diesel demand for the study period (2010-2050). It is estimated that an average mitigation of 0.0054 MT of CO₂ eq. per year can be achieved in this scenario. For fast penetration (2030) of scenario 15, the average reduction of diesel is 0.026 PJ year⁻¹ between 2010 and 2030, and the average reduction in GHG emissions is estimated to be 0.002 MT of CO₂ eq. per year by 2030. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.08 and 0.22 MT of CO₂ eq., respectively, with discounted incremental costs of -\$3.7 million and -\$6.2 million, respectively. Accordingly, the costs per unit of GHG mitigation are -45 and -28 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

Scenario 16: Ethanol Trucks (E-Tru)

For ethanol trucks, the reduction in gasoline demand for both slow and fast penetration is 85% per liter of E85 (for each liter of fuel, 85% of the gasoline is replaced with ethanol). Consequently, the net energy demand remains the same as in the reference scenario. The LEAP model estimates the average reduction in GHG emissions to be 0.003 MT of CO₂ eq. per year (2010-2050). For fast penetration of scenario 16, the average reduction in GHG emissions is estimated to be 0.0008 MT of CO₂ eq. per year by 2030. The incremental NPV of costs and net achievable GHG mitigation estimated by the LEAP model are presented in table 8. Total emissions for fast and slow penetration are 0.033 and 0.127 MT of CO₂ eq., respectively, with discounted incremental costs of \$64 million and \$6.3 million, respectively. Accordingly, the costs per unit of GHG mitigation are 1,941 and 50 (\$ tonne⁻¹ of CO₂ eq.) for fast and slow penetration, respectively (figs. 3 and 4).

IMPLICATIONS

We developed and analyzed 16 alternative scenarios for GHG mitigation in Alberta's agriculture sector. The results can inform farm owners and governments of the technologies that would be best for energy efficiency investment. Key results show that energy efficient livestock ventilation, lighting, waterers, electric irrigation, and electrical remote power systems in tractors offer both short-term and long-term negative GHG mitigation costs. The negative costs indicate a net benefit of investment due to saved energy costs. Of these technologies, the retrofits for efficient dairy, cattle, and hog ventilation, for electrical remote power systems in tractors, and for efficient waterers offer the greatest GHG mitigation with the best financial benefit in the short term. In the long term, biodiesel tractors and high-efficiency trucks and tractors offer the deepest GHG reductions of all scenarios and have negative mitigation costs. These identified scenarios are recommended for energy efficiency investment because they will yield a positive cash flow from saved energy. The identified scenarios are also recommended for policy formulation because public money spent

on these technologies will lead to the most effective GHG mitigation measures, both financially and environmentally.

The agriculture sector in Alberta was found to have an approximately 3% to 7% baseline mitigation potential by 2050, considering the energy-efficiency scenarios. The majority of mitigation potential by 2050 comes from three scenarios: efficient diesel tractors (7.1%), biodiesel tractors (2.3%), and electrical remote power systems in tractors (1.2%). If both the agriculture industry and government focus on these technologies, it is expected that GHG mitigation will be maximized and a net monetary benefit will be incurred from the investment. It should be noted that when comparing the absolute amount of GHG mitigation possible in the agriculture sector to other sectors, the agriculture sector has a relatively small amount due to its low overall GHG emissions.

SENSITIVITY ANALYSIS

A sensitivity analysis was completed for the 2009-2050 period. The sensitivity analysis is summarized in figures A-6 to A-39 in the Appendix. The inputs (CSE, discount rate, reference scenario growth rate, and energy intensity improvement) were varied by $\pm 30\%$. The results show that CSE has a 1:1 correlation with the GHG mitigation cost for each scenario. The discount rate has a large impact on the mitigation cost, especially for the biofuel-based scenarios. This is due to biofuels becoming increasingly economically attractive during the latter half of the study period. The reference scenario growth rate has a small ($<5\%$) effect on the mitigation cost for each scenario, with the exception of the biofuel-based scenarios, which show 73% to 171% change at 30% input variation. The reference scenario growth rate has a moderate impact on total mitigation potential, ranging from 13% to 21% output variation with 30% input variation. The assumptions for energy intensity improvements do not affect the mitigation cost. Varying the energy intensity by 30% has an average change of 40% in total mitigation potential from the baseline.

CONCLUSIONS

A Long-range Energy Alternatives Planning (LEAP) model was developed to evaluate the GHG mitigation potential and cost-benefits of energy-demand based GHG mitigation options for Alberta's agriculture sector. Energy demand and GHG emissions in the reference scenario were analyzed, and new scenarios were developed and modeled in LEAP to estimate the GHG mitigation potential and costs per tonne of mitigation. The identified mitigation potential in the agriculture sector represents a very small portion of total GHG emissions considering other sectors. Abatement costs for various mitigation scenarios were used to develop cost curves for both slow (by 2050) and fast (by 2030) penetration rates. The cost curves help evaluate the relative costs per tonne of GHG mitigated in a specified period and provide insights into the economic feasibility of the scenarios under consideration. Among the various mitigation options, efficiency improvements in farm equipment (i.e., biodiesel tractors, efficient diesel tractors, and electrical remote power

systems in tractors) showed the most promise for GHG mitigation. Biodiesel tractors and efficient diesel tractors showed the highest mitigation potential. The abatement costs of biodiesel combines and tractors as well as efficient diesel tractors are low, with considerable GHG mitigation potential, which makes this machinery economically and environmentally attractive. The framework developed in this study can be adopted to analyze GHG mitigation options in agriculture for other jurisdictions, with required modification of the input data. The results inform policy makers and agriculture businesses of the cost-benefits of various agriculture technologies.

ACKNOWLEDGEMENTS

The authors are grateful to Alberta Innovates (Clean Energy Division) and Alberta Agriculture and Forestry (AAF) for the financial support to carry out this project. The authors are also grateful to the NSERC/Cenovus/Alberta Innovates Associate Industrial Research Chair Program in Energy and Environmental Systems Engineering and the Cenovus Energy Endowed Chair Program in Environmental Engineering for the input to carry out the research. The authors would like to thank the steering committee for this project for their constant input and feedback during the term of the project. The steering committee included Brian Waddell, Barry Anderson, Marc Huot, and Steven Ottoni of Alberta Environment and Parks (AEP); Eddy Isaacs and Surindar Singh of Alberta Innovates, Clean Energy Division; and Menzie McEachern and Mike Ekelund of the Alberta Department of Energy (ADOE). The authors are thankful to Sheilah Nolan and Lawrence Papworth of Alberta Agriculture and Forestry (AAF) for their valuable inputs and suggestions. The authors are also thankful to Dr. Mohammad Khakbazan, agricultural economist at Agriculture and Agri-Food Canada, for guiding this study with his experience, along with staff at the Canadian Agricultural Energy End-Use Data and Analysis Center (CAEEDAC), Statistics Canada, and Natural Resources Canada (NRCan) for providing access to their reports and databases. The authors are grateful to many others in the several provincial and federal agencies and the engineering community who provided valuable input into the development of the greenhouse gas mitigation cost curves for Alberta. The authors are very thankful to Ms. Astrid Blodgett for editing the manuscript and to Matthew Davis for assistance with energy modeling. All conclusions, recommendations, and opinions are solely the authors' and are neither endorsed by the financial sponsor of this work nor by the many people who offered comments and suggestions.

REFERENCES

- A. O. Smith. (2012). BPD-75 tank type water heater with commercial natural gas. Milwaukee, WI: A. O. Smith Water Products.
- Balachandra, P., Nathan, H. S. K., & Reddy, B. S. (2010). Commercialization of sustainable energy technologies. *Renew. Energy*, 35(8), 1842-1851. <https://doi.org/10.1016/j.renene.2009.12.020>
- Billingsley, M. A., Hoffman, I. M., Stuart, E., Schiller, S. R., Goldman, C. A., & LaCommare, K. (2014). The program

- administrator cost of saved energy for utility customer-funded energy efficiency programs. Report No. LBNL-6595E. Berkeley, CA: Lawrence Berkeley National Laboratory. <https://doi.org/10.2172/1129528>
- Clarke, S., & Chambers, R. (2006). Energy efficient swine lighting factsheet. Guelph, ON: Ontario Ministry of Food, Agriculture, and Rural Affairs. Retrieved from <http://www.omafra.gov.on.ca/english/engineer/facts/06-011.htm>
- Clarke, S., & House, H. (2006). Energy efficient dairy lighting factsheet. Guelph, ON: Ontario Ministry of Food, Agriculture, and Rural Affairs. Retrieved from <http://www.omafra.gov.on.ca/english/engineer/facts/06-007.htm>
- Clarke, S., & Ward, D. (2006a). Energy efficient mechanical ventilation fan systems factsheet. Guelph, ON: Ontario Ministry of Food, Agriculture, and Rural Affairs. Retrieved from <http://www.omafra.gov.on.ca/english/engineer/facts/06-057.htm>
- Clarke, S., & Ward, D. (2006b). Energy efficient poultry lighting factsheet. Guelph, ON: Ontario Ministry of Food, Agriculture, and Rural Affairs. Retrieved from http://www.omafra.gov.on.ca/english/engineer/con_energy.htm
- Dill, G. (2010). Irrigation system energy trial assessment project. Final report. Lethbridge, AB: Alberta Agriculture and Rural Development.
- ECCC. (2017). National inventory report 1990-2015: Greenhouse gas sources and sinks in Canada. Gatineau, QC: Environment and Climate Change Canada.
- EIA. (1999). Annual energy outlook 2000 with projections to 2020. Washington, DC: Energy Information Administration.
- FAOSTAT. (2017). Emissions by sector. Rome, Italy: United Nations FAO. Retrieved from <http://www.fao.org/faostat/en/#data/EM>
- Friedrick, K., Eldridge, M., York, D., Witte, P., & Kushler, M. (2009). Saving energy cost effectively: A national review of cost of energy saved through utility sector energy efficiency program. Washington, DC: American Council for an Energy Efficient Economy.
- Golub, A., Hertel, T., Lee, H.-L., Rose, S., & Sohngen, B. (2009). The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. *Resour. Energy Econ.*, 31(4), 299-319. <https://doi.org/10.1016/j.reseneeco.2009.04.007>
- Jacobson, L. D., & Chastain, J. P. (1994). Fan performance and efficiency for animal ventilation systems. St. Paul, MN: University of Minnesota Extension. Retrieved from <https://www.extension.umn.edu/agriculture/manure-management-and-air-quality/air-quality/fan-performance-and-efficiency-for-animal-ventilation-systems/>
- Khakbazan, M. (2000). Descriptive analysis of on-farm energy use in Canada. Saskatoon, SK: University of Saskatchewan, Canadian Agricultural Energy End Use Data and Analysis Centre (CAEEDAC). Retrieved from <http://www.usask.ca/agriculture/caedac/pubs/Energy.PDF>
- Kong, L., Hasanbeigi, A., Price, L., & Liu, H. (2015). Energy conservation and CO₂ mitigation potentials in the Chinese pulp and paper industry. *Resour. Conserv. Recycl.*, 117(A), 74-84. <https://doi.org/10.1016/j.resconrec.2015.05.001>
- Kumar, A., Bhattacharya, S. C., & Pham, H. L. (2003). Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the Long-range Energy Alternative Planning system model. *Energy*, 28(7), 627-654. [https://doi.org/10.1016/S0360-5442\(02\)00157-3](https://doi.org/10.1016/S0360-5442(02)00157-3)
- Lal, R. (2016). Chapter 28: Climate change and agriculture. In T. M. Lectcher (Ed.), *Climate change: Observed impact on planet Earth* (pp. 465-489). Amsterdam, The Netherlands: Elsevier. <https://doi.org/10.1016/B978-0-444-63524-2.00028-2>
- Li, D., Watson, C. J., Yan, M. J., Lalor, S., Rafique, R., Hyde, B., ... Humphreys, J. (2013). A review of nitrous oxide mitigation by farm nitrogen management in temperate grassland-based agriculture. *J. Environ. Mgmt.*, 128, 893-903. <https://doi.org/10.1016/j.jenvman.2013.06.026>
- MAFRI. (2012). Farm machinery custom and rental rate guide. Winnipeg, MB: Manitoba Agriculture, Food, and Rural Initiatives.
- Malloy, G., & Lachapelle, M. (2012). Gas, hybrid, and electric: What you need to know. Ottawa, ON: Canadian Automobile Association. Retrieved from http://caa.ca/docs/eng/CAA_Engine_Technology_eBook_en.pdf
- McPherson, M., & Karney, B. (2014). Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy*, 68, 146-157. <https://doi.org/10.1016/j.enpol.2014.01.028>
- Meier, A. (1982). Supply curves of conserved energy. Berkeley, CA: Lawrence Berkeley National Laboratory.
- Mohareb, E., & Row, J. (2014). Improving energy efficiency in Alberta's buildings: Best practices, key actors, and the role of sustainable energy organizations. Calgary, AB: Pembina Institute.
- NEB. (2011). Canada's energy future: Energy supply and demand projections to 2035. Calgary, AB: National Energy Board.
- NRCAN. (2006). Canada's energy outlook: The reference case 2006. Cat. No. M144-126/2006E-PDF. Ottawa, ON: Natural Resources Canada, Analysis and Modeling Division.
- NRCAN. (2012a). Alternative fuel facts: Applications of ethanol. Alternative Fuels Report. Ottawa, ON: Natural Resources Canada. Retrieved from <http://www.nrcan.gc.ca/energy/alternative-fuels/3487>
- NRCAN. (2012b). Average retail price of regular gasoline. Energy Sources. Ottawa, ON: Natural Resources Canada. Retrieved from http://www2.nrcan.gc.ca/eneene/sources/pripri/prices_bycity_e_cfm?PriceYear=0&ProductID=1&LocationID=66,8,39,17#PriceGraph
- NRCAN. (2012c). Comprehensive energy use database. Ottawa, ON: Natural Resources Canada. Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm
- NRCAN. (2012d). Understanding gasoline markets in Canada. Fuel Focus Report. Ottawa, ON: Natural Resources Canada. Retrieved from <http://www.nrcan.gc.ca/sources/petroleum-crude-prices/gazoline-reports/4793>
- NRCAN. (2017). Light bulbs or lamps. Ottawa, ON: Natural Resources Canada. Retrieved from <http://www.nrcan.gc.ca/energy/products/categories/lighting/bulbs/13918>
- Navigant. (2009). Measures and assumptions for demand side management. Toronto, ON: Navigant Consulting, Inc., and the Ontario Energy Board.
- Nayak, D., Saetnan, E., Cheng, K., Wang, W., Koslowski, F., Cheng, Y.-F., ... Smith, P. (2015). Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agric. Ecosyst. Environ.*, 209, 108-124. <https://doi.org/10.1016/j.agee.2015.04.035>
- Nikos, A., & Jelle, B. (2012). World agriculture towards 2030/2050. Rome, Italy, United Nations FAO. Retrieved from www.fao.org/economic/esa
- Packey, D. J. (1993). Market penetration of new energy technologies. Golden, CO: National Renewable Energy Laboratory.
- Papworth, L. (2013). Feedlot watering case study. Lethbridge, AB: Alberta Agriculture and Rural Development, Agricultural Technology Centre.
- Papworth, L. (2014). Personal communication with Lawrence

- Papworth. Alberta Agriculture and Rural Development, Agricultural Technology Centre, Lethbridge, Alberta, Canada.
- Rogan, F., Cahill, C. J., Daly, H. E., Dineen, D., Deane, J. P., Heaps, C., ... Gallachoir, B. P. O. (2014). LEAPs and bounds: An energy demand and constraint optimised model of the Irish Energy System. *Energy Efficiency*, 7(3), 441-466. <https://doi.org/10.1007/s12053-013-9231-9>
- Schilling, M. A., & Esmundo, M. (2009). Technology S-curves in renewable energy alternatives: Analysis and implications for industry and government. *Energy Policy*, 37(5), 1767-1781. <https://doi.org/10.1016/j.enpol.2009.01.004>
- Schneider, U. A., & Smith, P. (2009). Energy intensities and greenhouse gas emission mitigation in global agriculture. *Energy Efficiency*, 2(2), 195-206. <https://doi.org/10.1007/s12053-008-9035-5>
- Shabbir, R., & Ahmad, S. S. (2010). Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using LEAP model. *Energy*, 35(5), 2323-2332. <https://doi.org/10.1016/j.energy.2010.02.025>
- Sieniewicz, O. (2012). Tankless or on demand hot water heater. Edmonton, AB: Alberta Agriculture and Rural Development.
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., ... Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Phil. Trans. Royal Soc. B*, 363(1492), 789-813. <https://doi.org/10.1098/rstb.2007.2184>
- Statistics Canada. (2009). 2006 census of agriculture. Ottawa, ON: Statistics Canada. Retrieved from <http://www.statcan.gc.ca/cara2006/analysis-analyses/alberta-eng.htm>
- Statistics Canada. (2012). CANSIM table. Ottawa, ON: Statistics Canada. Retrieved from <http://www5.statcan.gc.ca/cansim/home-accueil?lang=eng&p2=50&HPA>
- Stewart, B., Veeman, T., & Unterschultz, J. (2009). Crops and livestock productivity growth in the prairies: The impacts of technical change and scale. *Canadian J. Agric. Econ.*, 57(3), 379-394. <https://doi.org/10.1111/j.1744-7976.2009.01157.x>
- SEI. (2011). LEAP: Long-range energy alternatives planning system user guide for version 2011. Somerville, MA: Stockholm Environment Institute. Retrieved from <http://www.energycommunity.org/documents/LEAP2011UserGuideEnglish.pdf>
- Subramanyam, V., Paramashivan, D., Radpour, S., Shah, T., & Kumar, A. (2013). Identification of best energy-efficiency opportunities in Alberta's energy sector PHASE II. Edmonton, AB: Alberta Innovates - Energy and Environmental Solutions (AIEES).
- Subramanyam, V., Paramashivan, D., Kumar, A., & Mondal, M. A. (2015). Using Sankey diagrams to map energy flow from primary fuel to end use. *Energy Conv. Mgmt.*, 91, 342-352. <https://doi.org/10.1016/j.enconman.2014.12.024>
- Sundby, W. (2013). Personal communication with W. Sundby, Western Canada District Manager, GSI Electronics, Inc., Saint-Hubert, Quebec, Canada.
- CALSTART. (2010). The economic costs and benefits of improving the fuel economy of heavy-duty vehicles. Pasadena, CA: CALSTART.
- UN. (2015). World population prospects: The 2015 revision. New York, NY: United Nations.
- USDOE. (2003). Just the basics: Diesel engine. Washington, DC: U.S. Department of Labor, Office of Energy Efficiency and Renewable Energy. Retrieved from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/basics/jtb_diesel_engine.pdf
- USDOE. (2008). Clean cities. Biodiesel fact sheet. Washington, DC: U.S. Department of Labor, Office of Energy Efficiency and Renewable Energy. Retrieved from <http://www1.eere.energy.gov/cleancities/>
- USDOE. (2011). Clean Cities Alternative Fuel Price Report. Washington, DC: U.S. Department of Labor, Office of Energy Efficiency and Renewable Energy. Retrieved from https://www.afdc.energy.gov/pdfs/afpr_jul_11.pdf
- USDOE. (2013). Alternative fuels data center: Ethanol. Washington, DC: U.S. Department of Labor, Office of Energy Efficiency and Renewable Energy. Retrieved from <http://www.afdc.energy.gov/fuels/ethanol.html>
- Wang, W., Koslowski, F., Nayak, D. R., Smith, P., Saetan, E., Ju, X., ... Moran, D. (2014). Greenhouse gas mitigation in Chinese agriculture: Distinguishing technical and economic potentials. *Global Environ. Change*, 26, 53-62. <https://doi.org/10.1016/j.gloenvcha.2014.03.008>
- WEC. (2011). Global transport scenarios 2050. London, UK: World Energy Council. Retrieved from https://www.worldenergy.org/wp-content/uploads/2012/09/wec_transport_scenarios_2050.pdf
- Yolo County. (2011). Yolo County climate action plan: A strategy for smart growth implementation, greenhouse gas reduction, and adaptation to global climate change. Woodland, CA: Government of Yolo County.

APPENDIX
SUPPLEMENTARY DATA

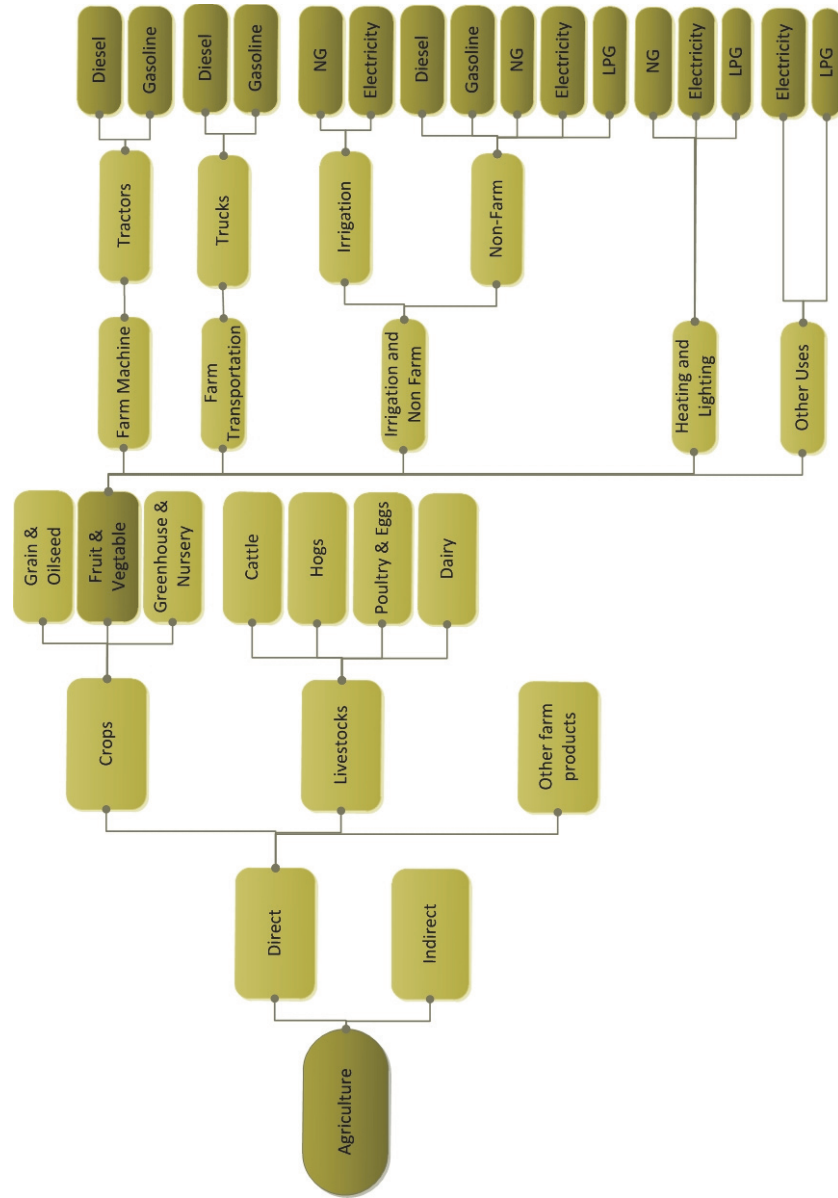


Figure A-1. Alberta's crop sector with the fruit and vegetable subsector.

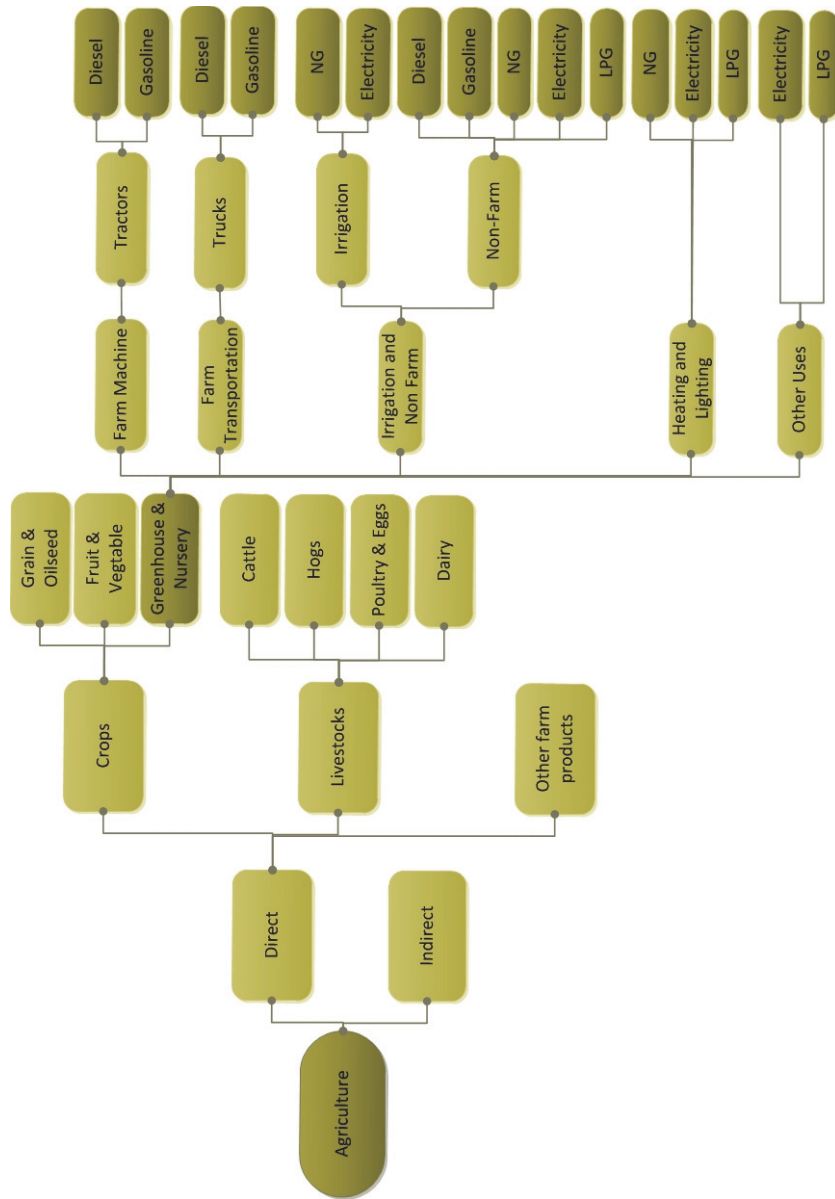


Figure A-2. Alberta's crop sector with the greenhouse and nursery subsector.

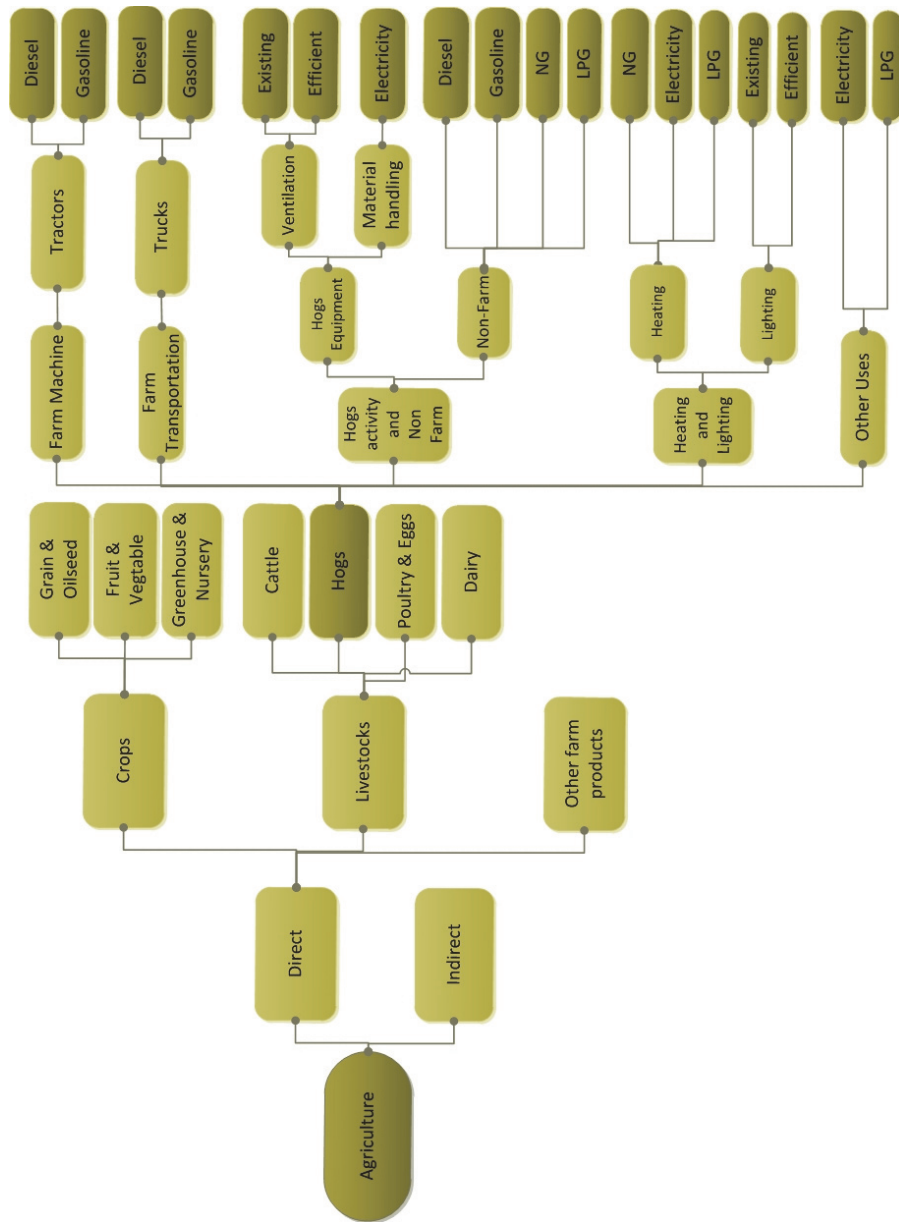


Figure A-3. Alberta's livestock sector with the hog subsector.

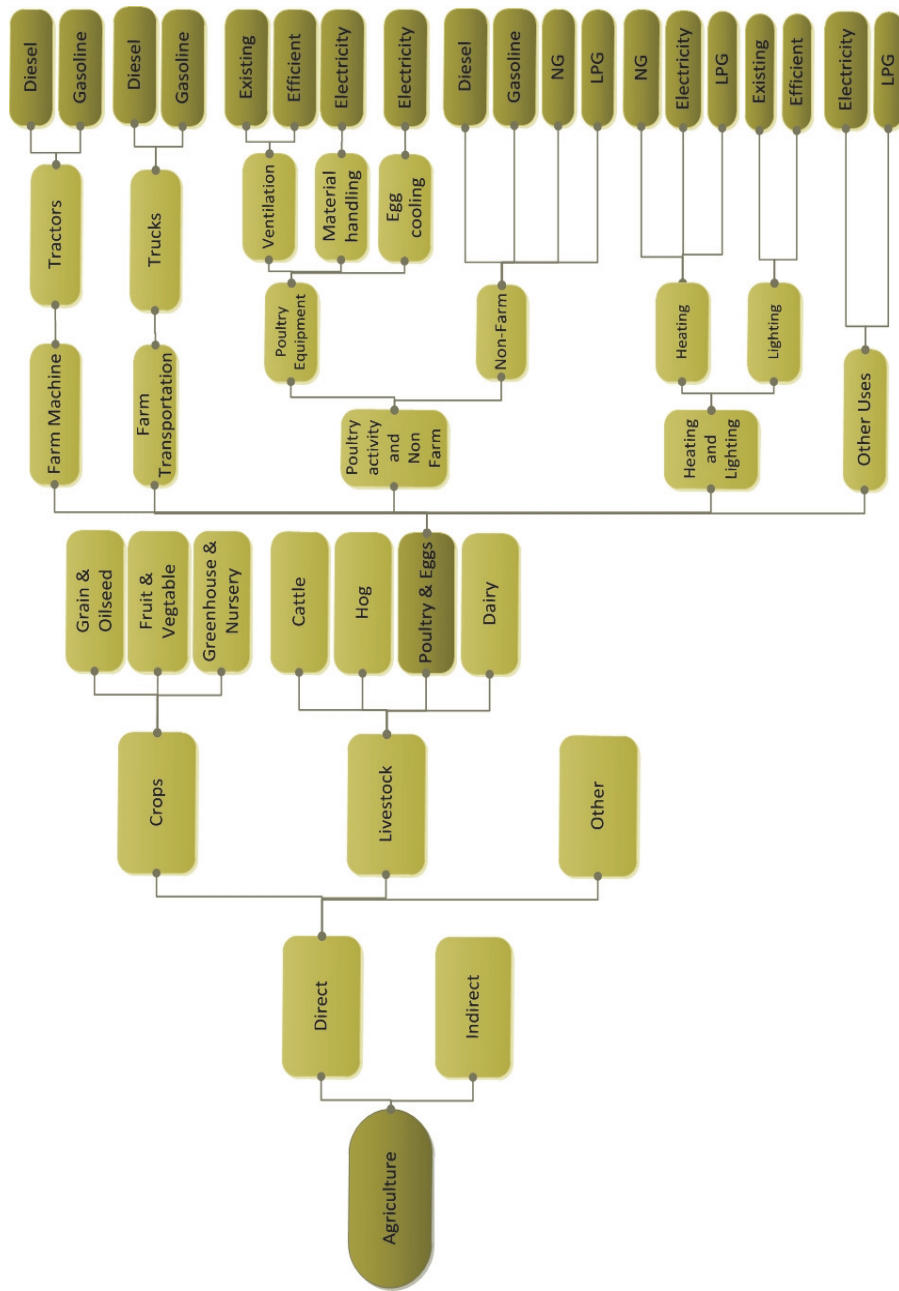


Figure A-4. Alberta's livestock sector with the poultry and eggs subsector.

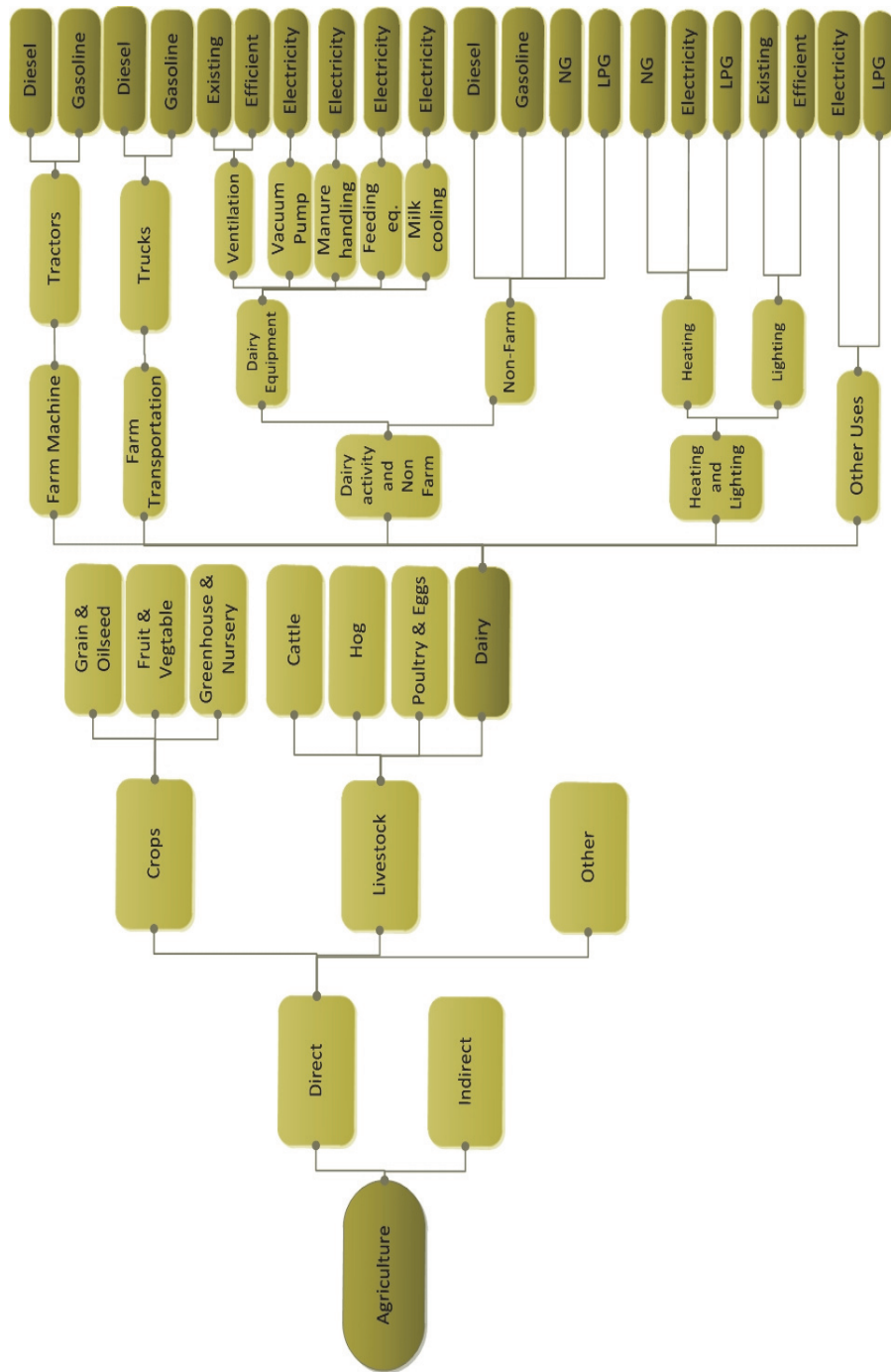


Figure A-5. Alberta's livestock sector with the dairy subsector.

Table A-1. Energy demand (base year fuel use in TJ) for Alberta's grain and oilseed subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	8,551	0	920	0	0
Farm transport	261	0	791	0	0
Non-farm	119	599	59	16	883
Heat and light	0	447	0	13	456
Other uses	0	209	0	27	0
Total	8,930	1,255	1,770	56	1,340

Table A-2. Energy demand (base year fuel use in TJ) for Alberta's fruit and vegetable subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	89	0	10	0	0
Farm transport	3	0	9	0	0
Non-farm	3	13	13	0	19
Heat and light	0	11	0	0	11
Other uses	0	10	0	1	0
Total	94	34	31	2	30

Table A-3. Energy demand (base year fuel use in TJ) for Alberta's greenhouse and nursery subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	50	0	5	0	0
Farm transport	5	0	15	0	0
Non-farm	17	86	86	2	128
Heat and light	0	122	0	3	123
Other uses	0	15	0	2	0
Total	72	223	106	8	250

Table A-4. Energy demand (base year fuel use in TJ) for Alberta's cattle subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	11,033	0	1,186	0	0
Farm transport	458	0	1,390	0	0
Non-farm	182	923	913	26	1,362
Heat and light	0	779	0	22	784
Other uses	0	326	0	41	0
Total	11,672	2,028	3,489	90	2,147

Table A-5. Energy demand (base year fuel use in TJ) for Alberta's hog subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	645	0	69	0	0
Farm transport	23	0	70	0	0
Non-farm	15	75	74	2	111
Heat and light	0	231	0	7	232
Other uses	0	15	0	2	0
Total	683	320	214	11	343

Table A-6. Energy demand (base year fuel use in TJ) for Alberta's poultry and eggs subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	192	0	21	0	0
Farm transport	15	0	46	0	0
Non-farm	10	51	50	1	75
Heat and light	0	368	0	10	370
Other uses	0	24	0	3	0
Total	217	443	117	15	445

Table A-7. Energy demand (base year fuel use in TJ) for Alberta's dairy subsector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	1,014	0	109	0	0
Farm transport	23	0	70	0	0
Non-farm	14	71	70	2	105
Heat and light	0	185	0	5	186
Other uses	0	66	0	8	0
Total	1,051	322	249	16	291

Table A-8. Energy demand (base year fuel use in TJ) for Alberta's "other" sector as developed by the LEAP model.

	Diesel	Electricity	Gasoline	LPG	NG
Farm machine	486	0	52	0	0
Farm transport	129	0	393	0	0
Non-farm	92	469	465	13	694
Heat and light	0	600	0	16	605
Other uses	0	211	0	27	0
Total	708	1,281	910	56	1,298

Table A-9. Increase in GHG emissions (MT CO₂ eq.) for Alberta agriculture's crop sector as developed by the LEAP model.

GHG Emissions	2009	2020	2030	2040	2050
Non-biogenic CO ₂	0.89	1.21	1.6	2.11	2.78
Methane	0.01	0.01	0.01	0.01	0.02
Nitrous oxide	0.01	0.01	0.01	0.01	0.02
Total	0.9	1.23	1.62	2.13	2.82

Table A-10. Increase in GHG emissions (MT CO₂ eq.) for Alberta agriculture's livestock sector as developed by the LEAP model.

GHG Emissions	2009	2020	2030	2040	2050
Non-biogenic CO ₂	1.47	1.79	2.15	2.58	3.1
Methane	0.01	0.01	0.01	0.02	0.02
Nitrous oxide	0.01	0.01	0.01	0.02	0.02
Total	1.49	1.82	2.18	2.61	3.14

Table A-11. Increase in GHG emissions (MT CO₂ eq.) for Alberta agriculture's "other" sector as developed by the LEAP model.

GHG Emissions	2009	2020	2030	2040	2050
Non-biogenic CO ₂	0.19	0.26	0.34	0.45	0.59
Methane	0	0	0	0	0
Nitrous oxide	0	0	0	0	0
Total	0.19	0.26	0.34	0.45	0.6

Table A-12. Total fuel-based emissions (MT CO₂ eq.) for Alberta agriculture's energy demand as developed by the LEAP model.

Fuel	2009	2020	2030	2040	2050
Diesel	1.74	2.22	2.78	3.49	4.39
Gasoline	0.48	0.62	0.77	0.97	1.22
LPG	0.02	0.02	0.03	0.04	0.05
Natural gas	0.34	0.44	0.56	0.7	0.89
Total	2.58	3.3	4.14	5.2	6.55

Table A-13. Cost assumptions for GHG mitigation scenarios.

Scenario Number and Name	Specifications	Efficiency	Operating Life (years)	Capital Cost ^[a] (2009)	Reference
1 Poultry efficient lighting (PL-CFL)	One farm (building) with 4380 h year ⁻¹ of operation; incandescent bulbs = 7570 kWh year ⁻¹ total; CFLs = 2840 kWh year ⁻¹ total; number of fixtures = 54.	Incandescent bulbs = 20%; CFLs = 80%	4	39	Clarke and Ward, 2006b
2 Poultry efficient lighting (PL-T8)	One farm (building) with 4380 h year ⁻¹ of operation; incandescent bulbs = 7570 kWh year ⁻¹ total; T8 = 2840 kWh year ⁻¹ total; number of fixtures = 54.	Incandescent bulbs = 20%; T8 = 88%	6	491	Clarke and Ward, 2006b
3 Dairy and cattle efficient lighting (DCL-T8)	One farm (building) with 6570 h year ⁻¹ of operation; incandescent bulbs = 20,126 kWh year ⁻¹ total; T8 = 5362 kWh year ⁻¹ total; number of fixtures = 30 for incandescent and 20 for T8.	Incandescent bulbs = 20%; T8 = 88%	6	384	Clarke and House, 2006
4 Swine/hog efficient lighting (SL-8)	One farm (building) with 2555 h year ⁻¹ of operation; incandescent bulbs = 3106 kWh year ⁻¹ total; T8 = 766 kWh year ⁻¹ total; number of fixtures = 53 for incandescent and 38 for T8.	Incandescent bulbs = 20%; T8 = 88%	6	75	Clarke and Chambers, 2006
5 Dairy, cattle, and hog efficient ventilation (DCH-EV)	One sample livestock farm (building); 100 animals for one farm; 6,000 square feet for 60 animals; five fans for 6,000 square feet and for 60 animals.	Fan A = 8.4 Fan B = 18.6 cfm W ⁻¹	10	162	Clarke and Ward, 2006a; Sundby, 2013
6 Poultry efficient ventilation (P-EV)	One sample poultry farm (building); 20,000 birds for one farm; 1.5 ft ² for one bird; 16 fans for every 16,000 ft ² ; six fans for 1500 ft ² and for 1000 birds.	Fan A = 8.4 Fan B = 18.6 cfm W ⁻¹	10	324	Clarke and Ward, 2006a; Sundby, 2013
7 Efficient diesel tractors (EFF-Trac)	Total tractors = 155,808; capital cost of new tractors = \$55,000; capital cost of old tractors = \$50,000.	20% efficiency improvement	15	482	Yolo County, 2011
8 Biodiesel tractors (Bio-Trac)	Total tractors = 155,808; total production = 33,284,859 tonnes; tonnes per tractor = 214.	n/a	15	0	Yolo County, 2011; USDOE, 2008
9 Biodiesel combines (Bio-Com)	Total combines = 26,576; total production = 33,284,859 tonnes; tonnes per combine = 1252.	n/a	15	0	MAFRI, 2012
10 Tankless water heaters in dairy (TL-D)	AO Smith BPD-75 tank-type water heater with commercial natural gas.	NG savings = 11,6000 GJ year ⁻¹	12	544	Smith, 2012
11 Electrical remote power systems in tractors (Ele-R)	Total operating hours per year = 300; capital cost of new system = \$55,000; capital cost of old system = \$50,000.	20% reduction in demand for diesel	15	482	Yolo County, 2011
12 Energy efficiency improvement in irrigation systems (IRR-E/IRR-NG)	Replacing pumps and motors with more efficient devices.	29%/36% energy savings per year	10	130/453	Dill, 2010
13 Energy-efficient waterers in cattle (EF-W)	Estimated 1716 kWh year ⁻¹ energy savings.	n/a	12	0	Papworth, 2013
14 Biodiesel trucks (Bio-Tru)	Total number = 135,752; total average in base year = 42,000,000 km; km per truck = 309.	n/a	12	0	CALSTART, 2010
15 High-efficiency diesel trucks (HEV-Tru)	Total number = 135,752; total average in base year = 42,000,000 km; km per truck = 309.	20% efficiency improvement	12	584	CALSTART, 2010
16 Ethanol trucks (E-Tru)	Total share of gasoline trucks = 5%; km per truck = 309.	n/a	12	0	CALSTART, 2010

^[a] Capital costs are incremental compared to the base year (2009) and annualized over the operating life at 5% interest.

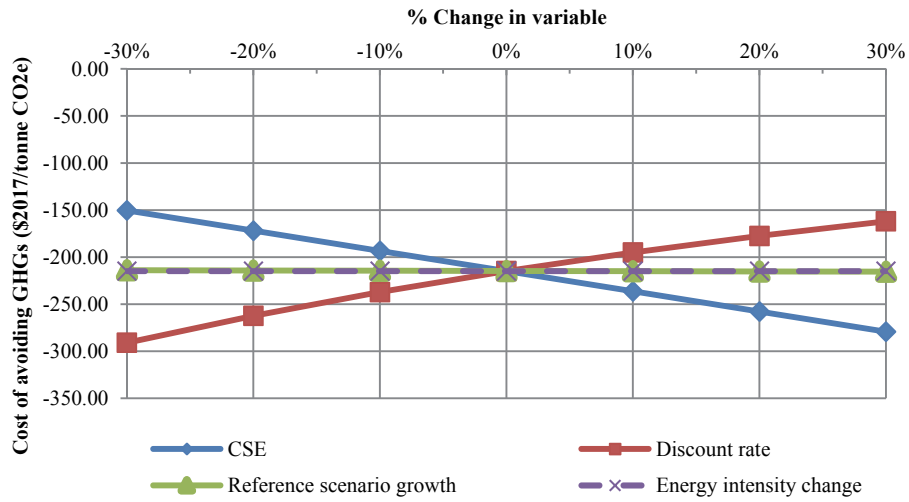


Figure A-6. Scenario 1 (PL-CFL) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

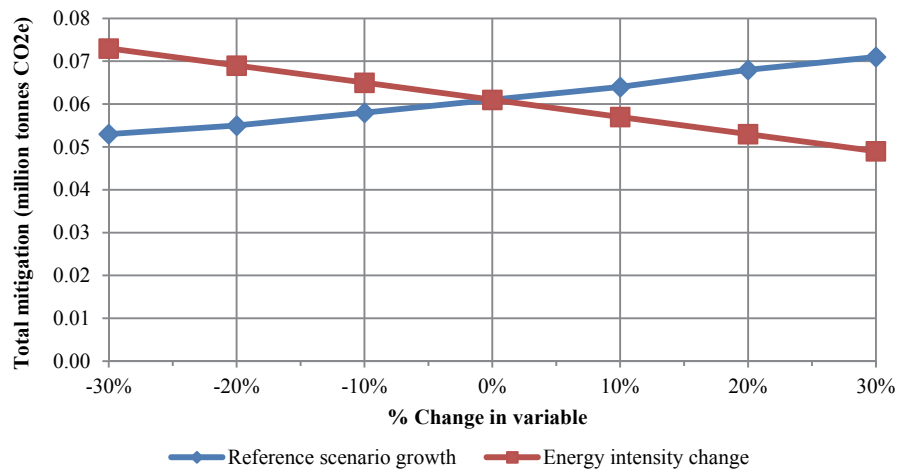


Figure A-7. Scenario 1 (PL-CFL) sensitivity analysis for mitigation potential (2009-2050).

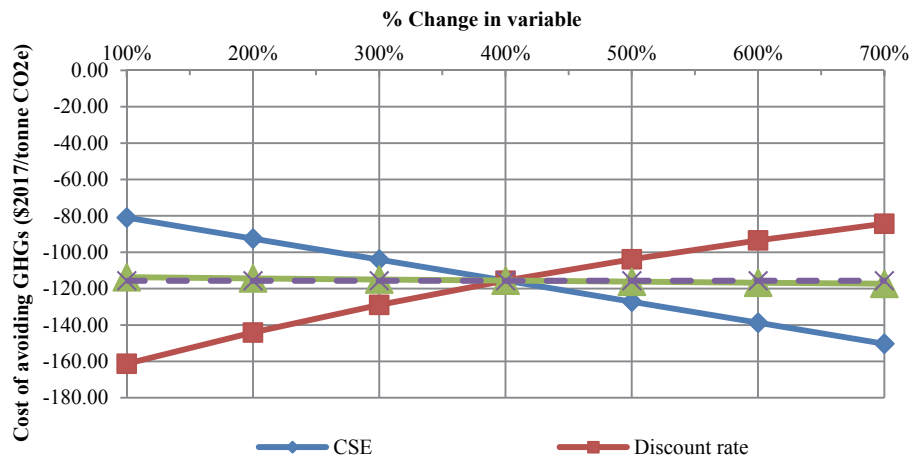


Figure A-8. Scenario 2 (PL-T8) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

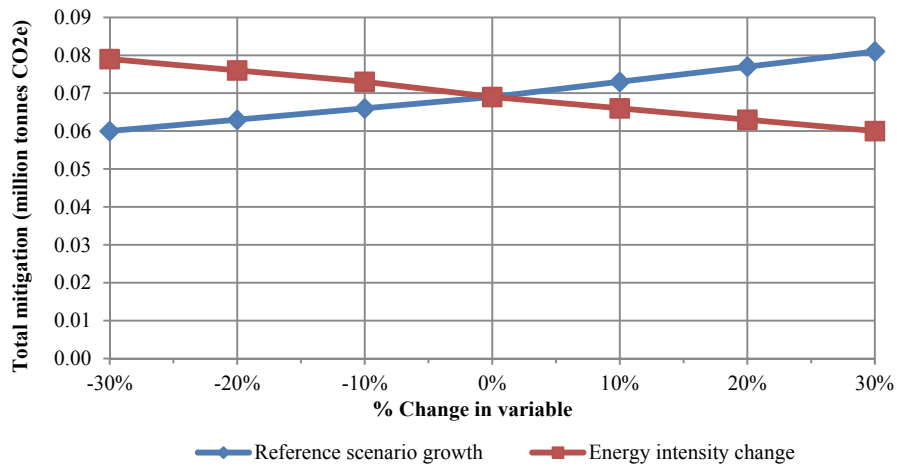


Figure A-9. Scenario 2 (PL-T8) sensitivity analysis for mitigation potential (2009-2050).

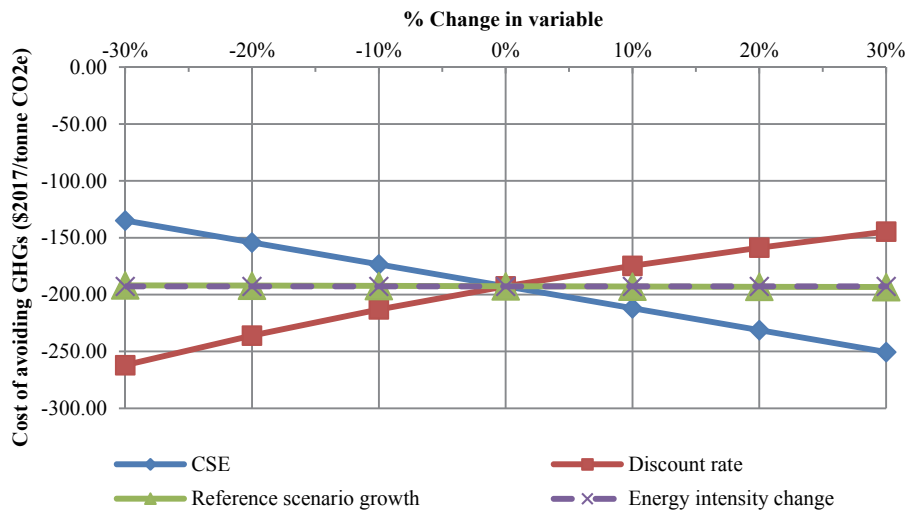


Figure A-10. Scenario 3 (DCL-T8) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

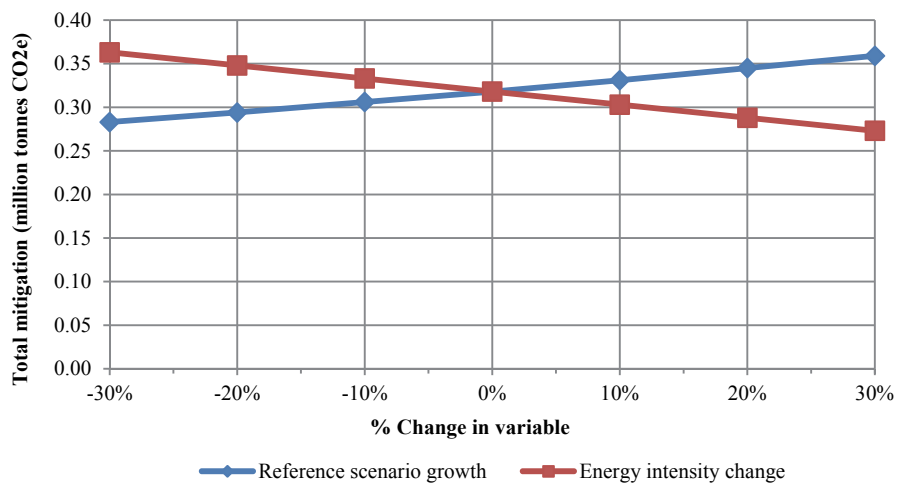


Figure A-11. Scenario 3 (DCL-T8) sensitivity analysis for mitigation potential (2009-2050).

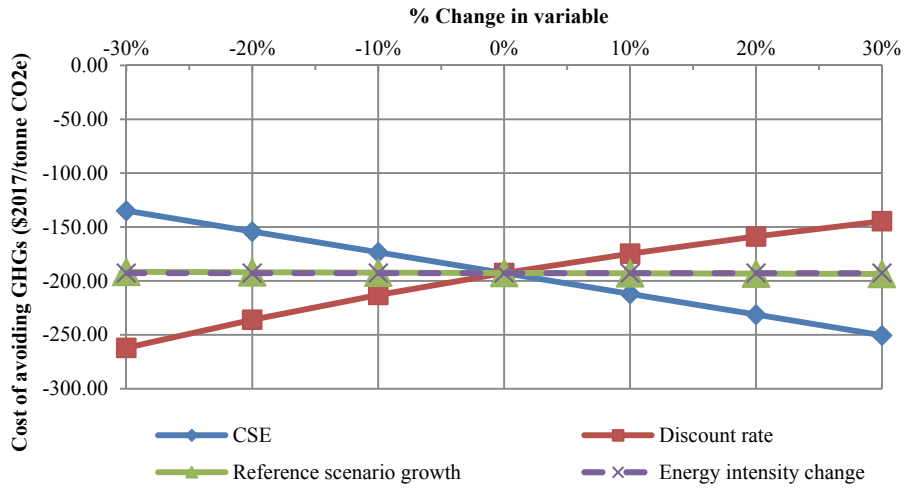


Figure A-12. Scenario 4 (SL-T8) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

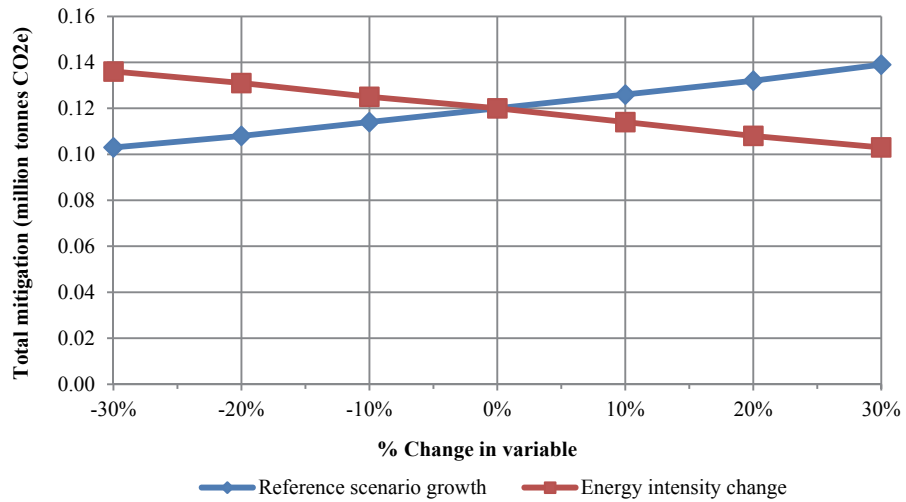


Figure A-13. Scenario 4 (SL-T8) sensitivity analysis for mitigation potential (2009-2050).

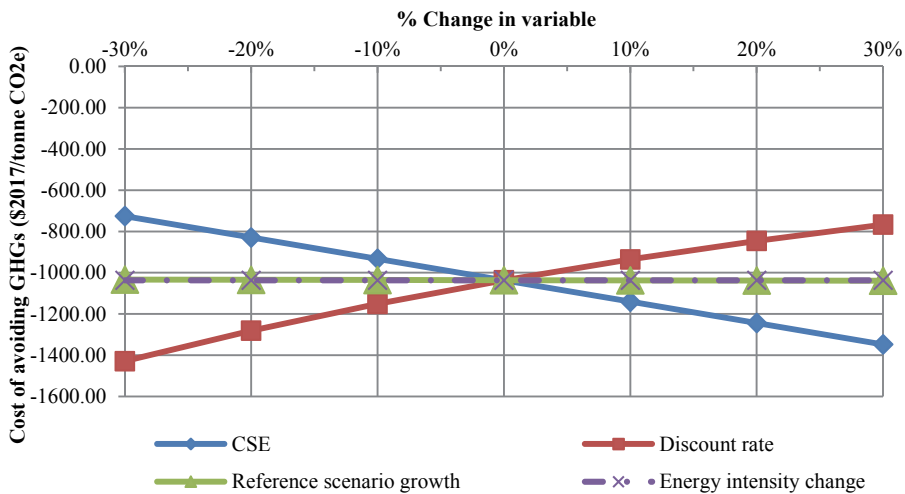


Figure A-14. Scenario 5 (DCH-EV) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

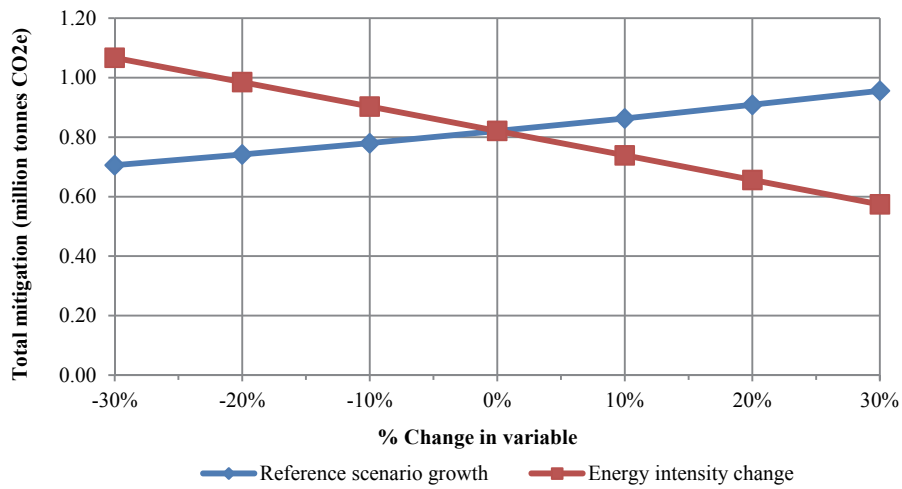


Figure A-15. Scenario 5 (DCH-EV) sensitivity analysis for mitigation potential (2009-2050).

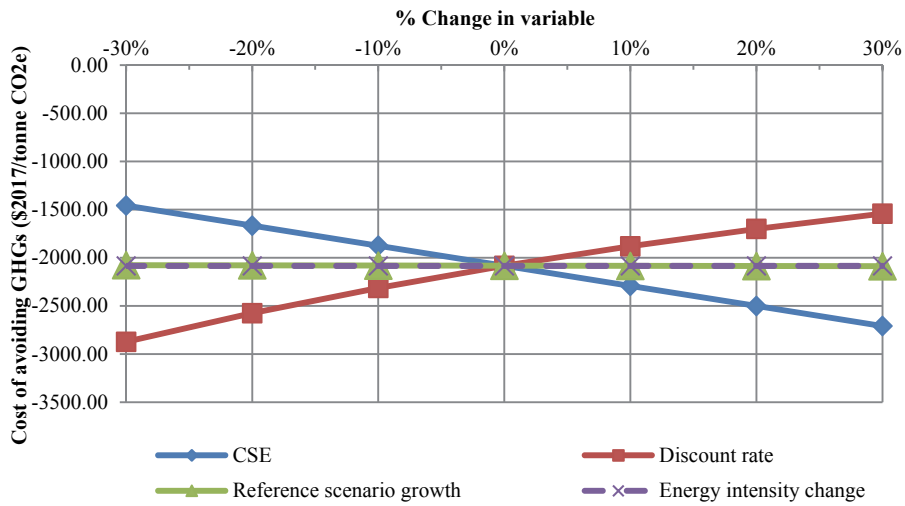


Figure A-16. Scenario 6 (PEV) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

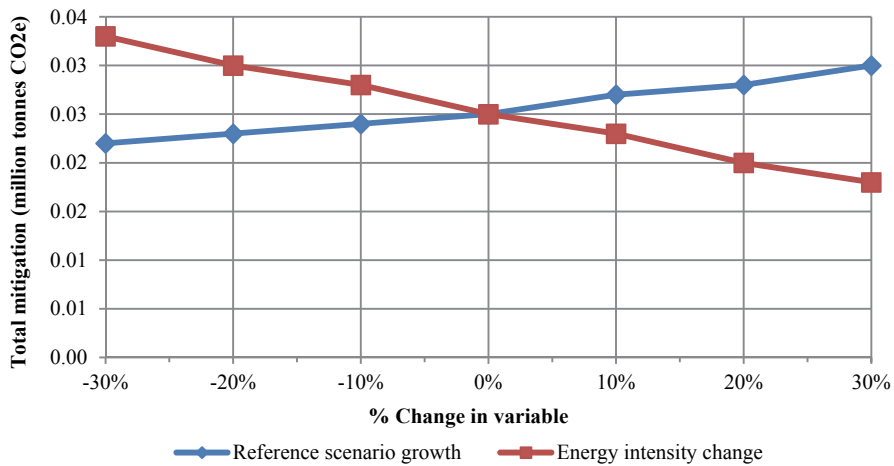


Figure A-17. Scenario 6 (PEV) sensitivity analysis for mitigation potential (2009-2050).

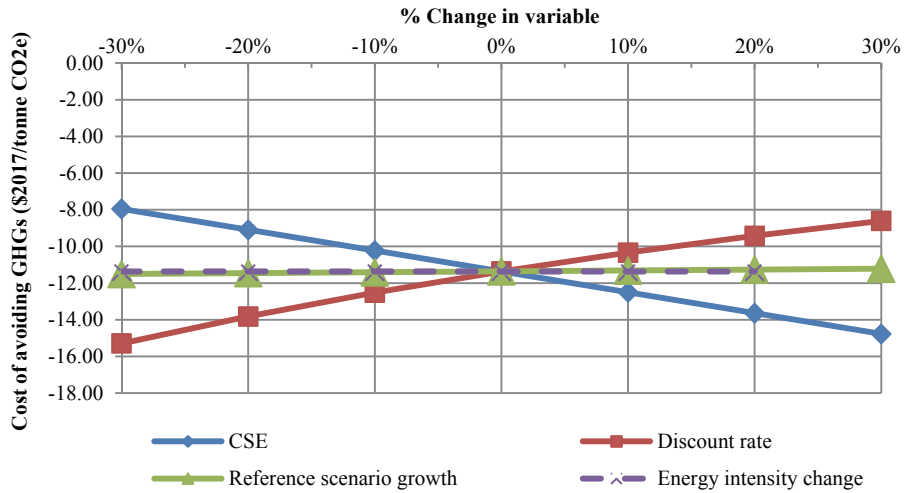


Figure A-18. Scenario 7 (EFF-Trac) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

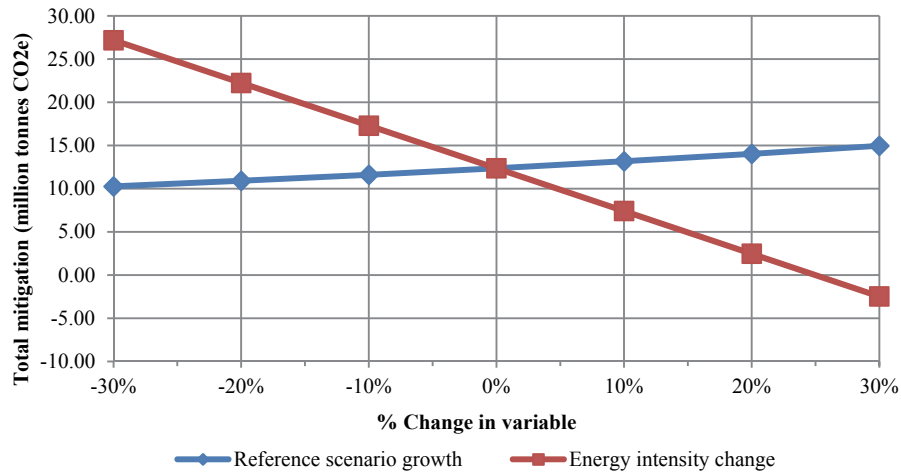


Figure A-19. Scenario 7 (EFF-Trac) sensitivity analysis for mitigation potential (2009-2050).

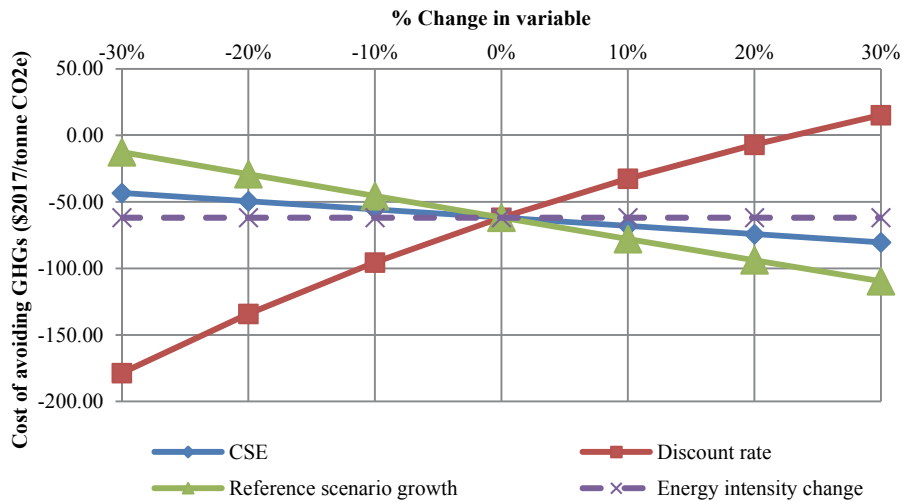


Figure A-20. Scenario 8 (Bio-Trac) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

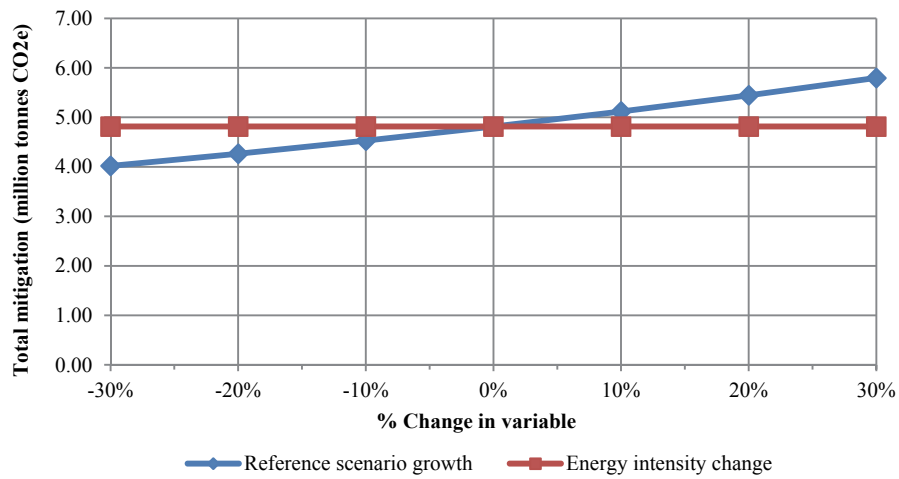


Figure A-21. Scenario 8 (Bio-Trac) sensitivity analysis for mitigation potential (2009-2050).

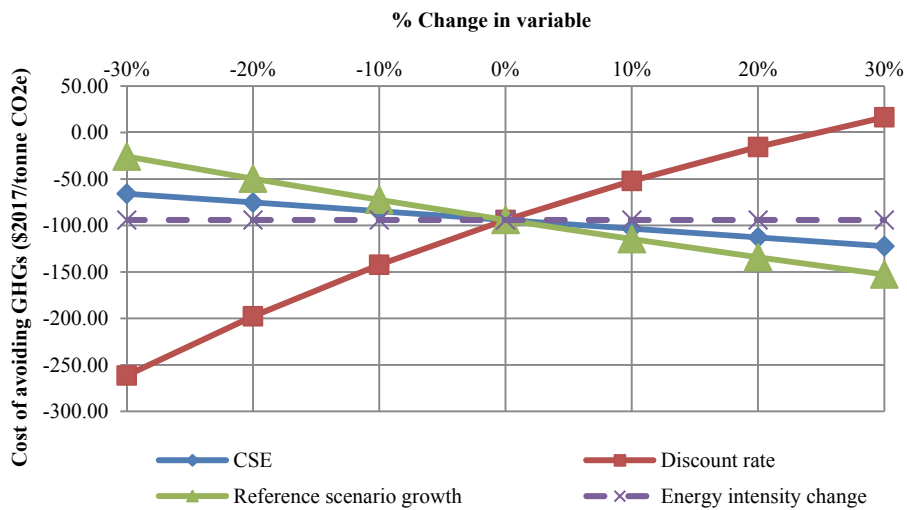


Figure A-22. Scenario 9 (Bio-Com) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

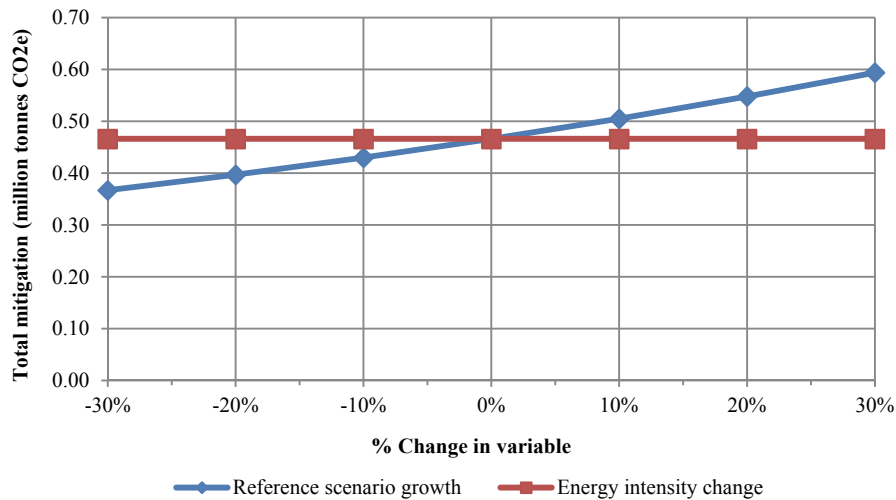


Figure A-23. Scenario 9 (Bio-Com) sensitivity analysis for mitigation potential (2009-2050).

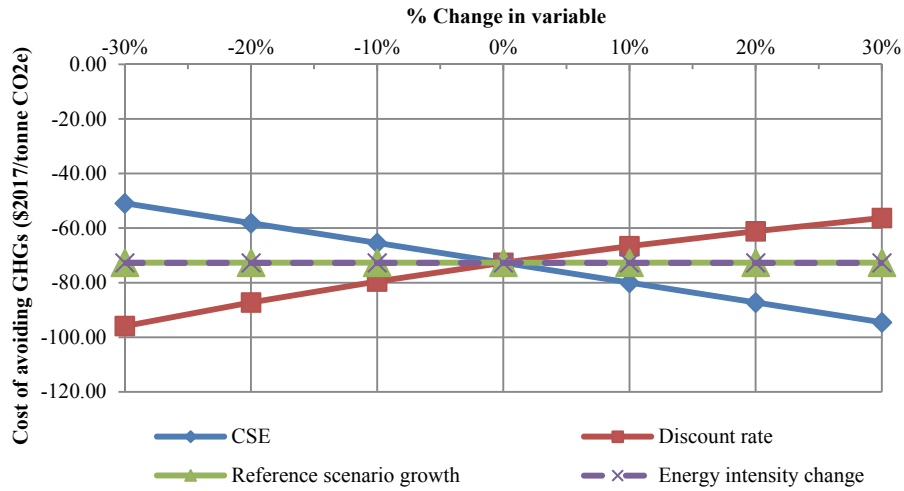


Figure A-24. Scenario 10 (TL-D) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

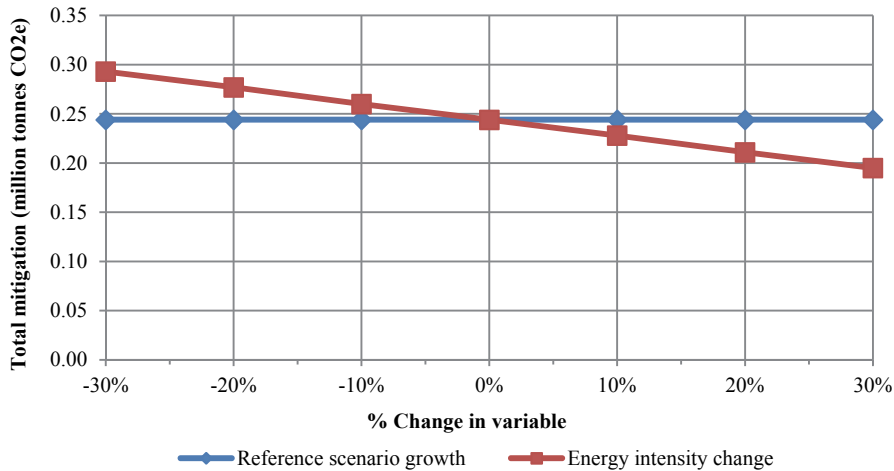


Figure A-25. Scenario 10 (TL-D) sensitivity analysis for mitigation potential (2009-2050).

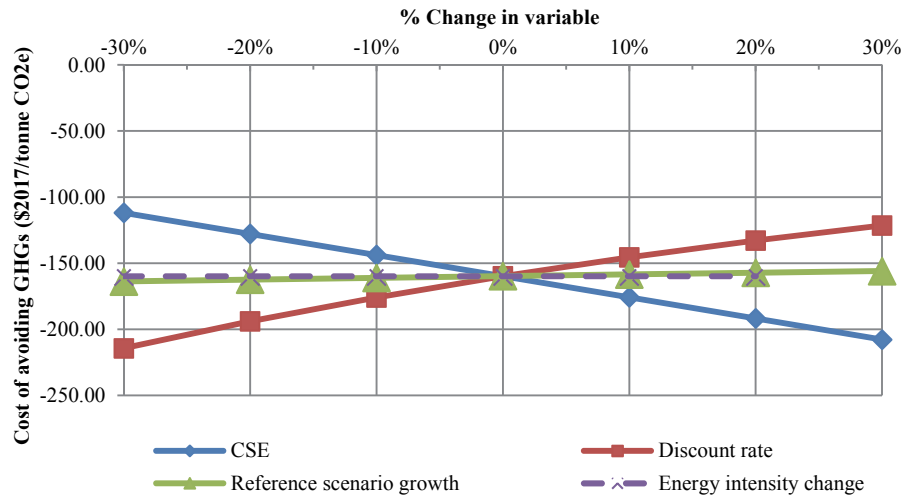


Figure A-26. Scenario 11 (Ele-R) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

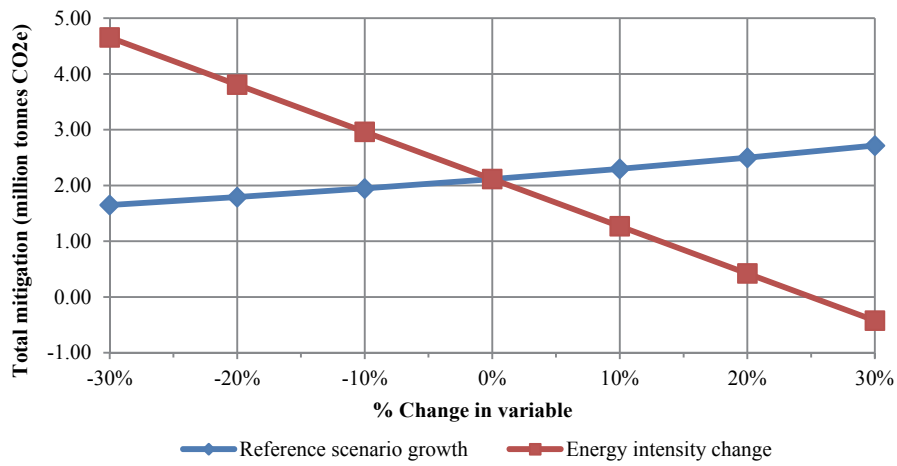


Figure A-27. Scenario 11 (Ele-R) sensitivity analysis for mitigation potential (2009-2050).

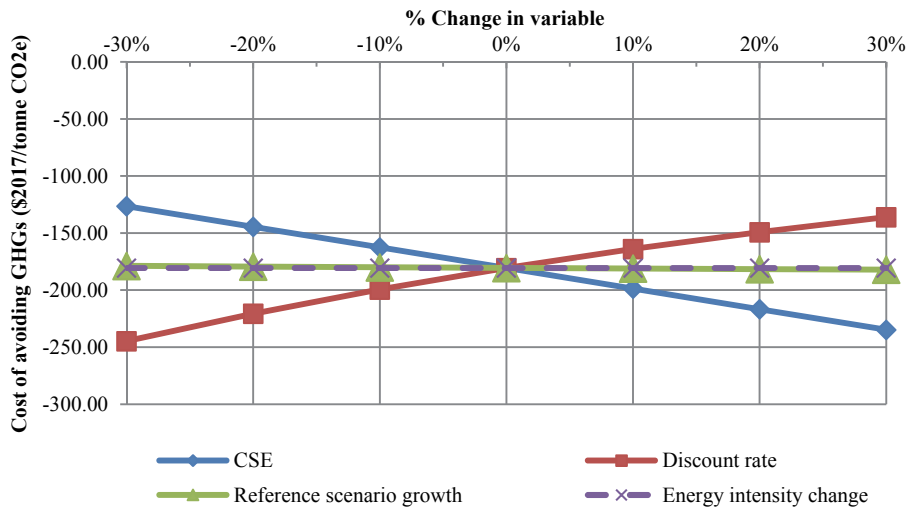


Figure A-28. Scenario 12 (IRR-E) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

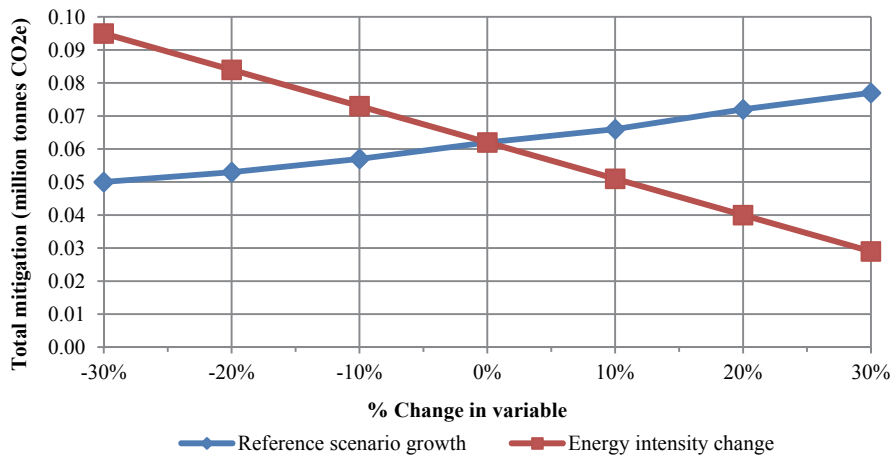


Figure A-29. Scenario 12 (IRR-E) E sensitivity analysis for mitigation potential (2009-2050).

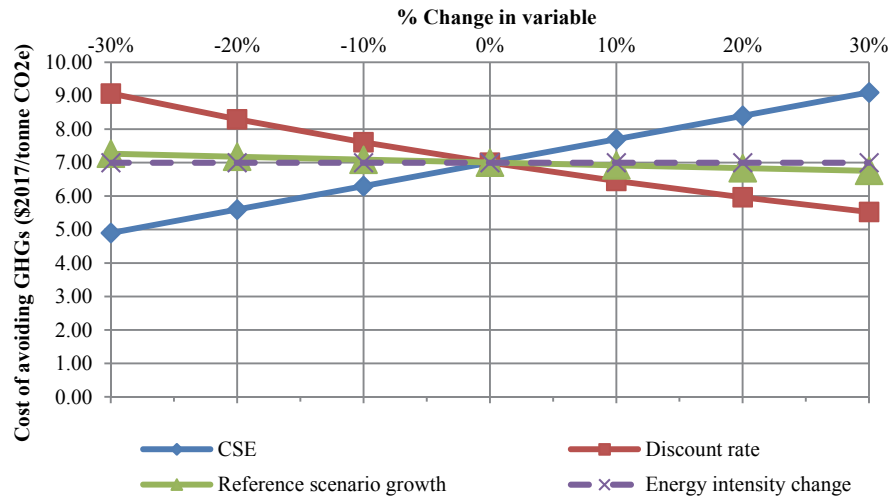


Figure A-30. Scenario 12 (IRR-NG) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

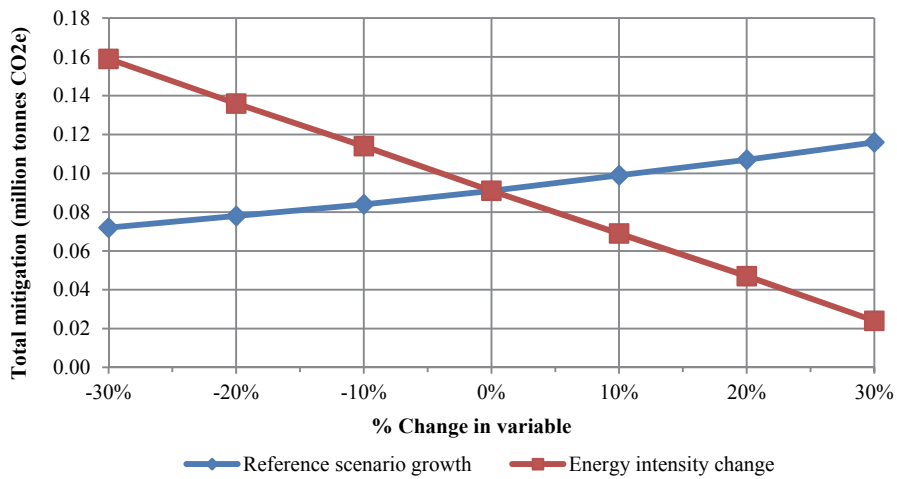


Figure A-31. Scenario 12 (IRR-NG) sensitivity analysis for mitigation potential (2009-2050).

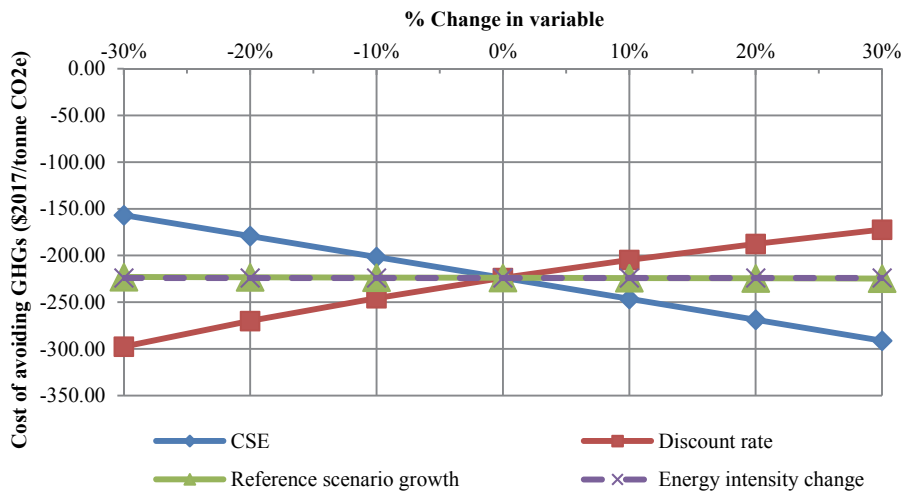


Figure A-32. Scenario 13 (EF-W) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

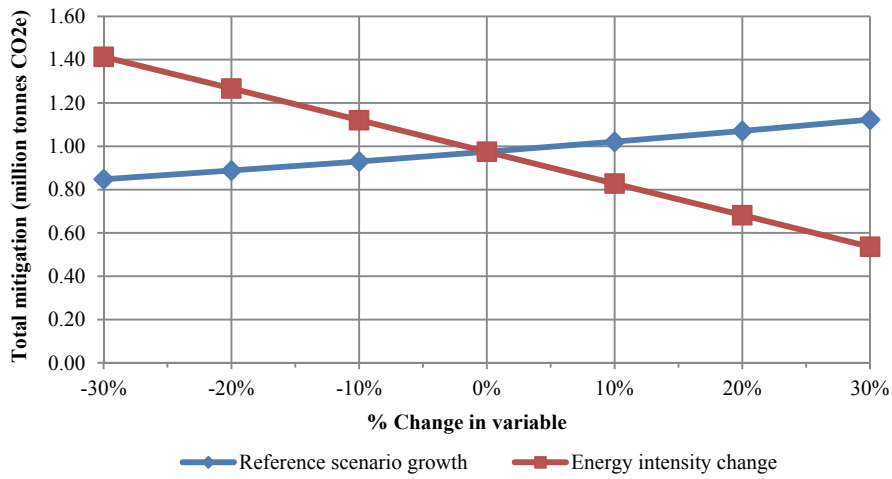


Figure A-33. Scenario 13 (EF-W) sensitivity analysis for mitigation potential (2009-2050).

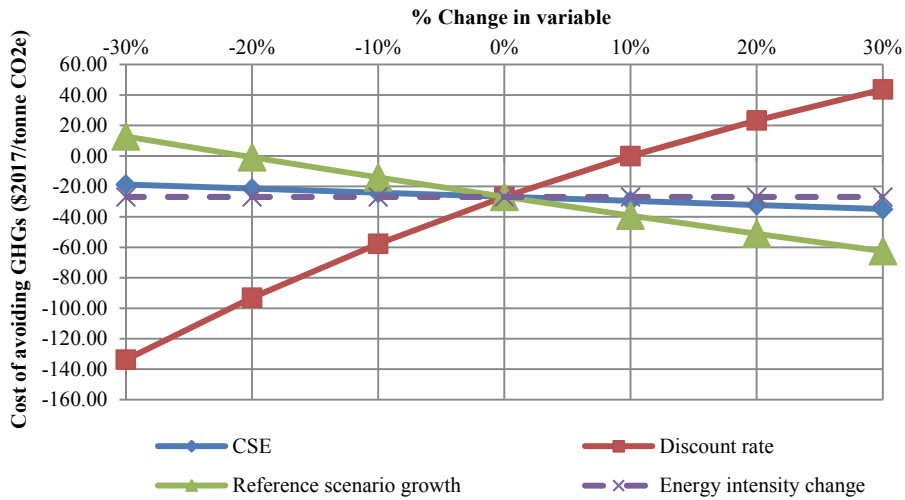


Figure A-34. Scenario 14 (Bio-Tru) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

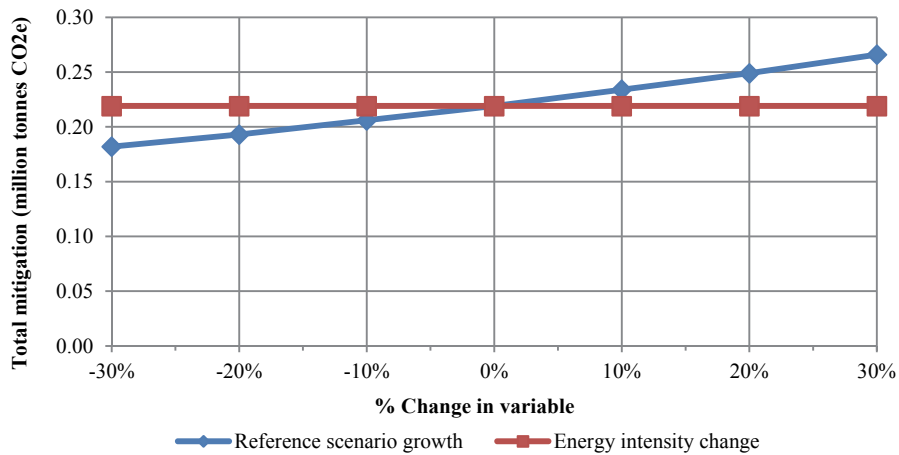


Figure A-35. Scenario 14 (Bio-Tru) sensitivity analysis for mitigation potential (2009-2050).

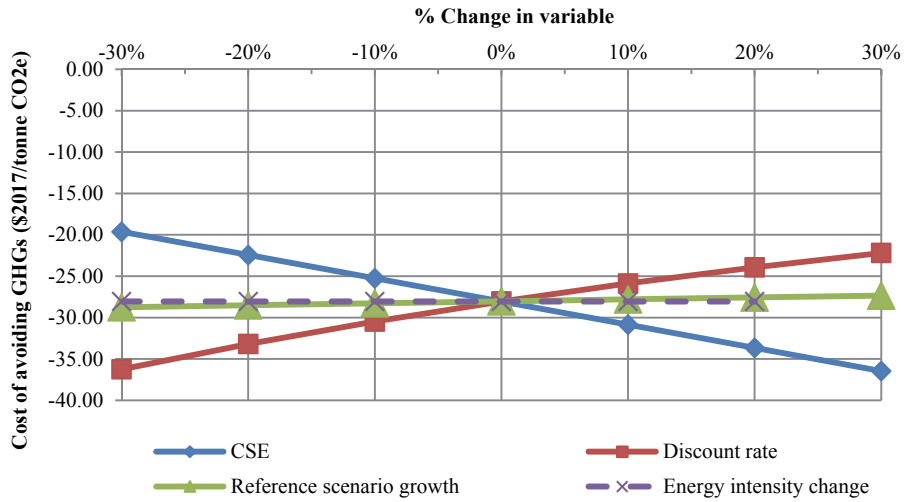


Figure A-36. Scenario 15 (HEV-Tru) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

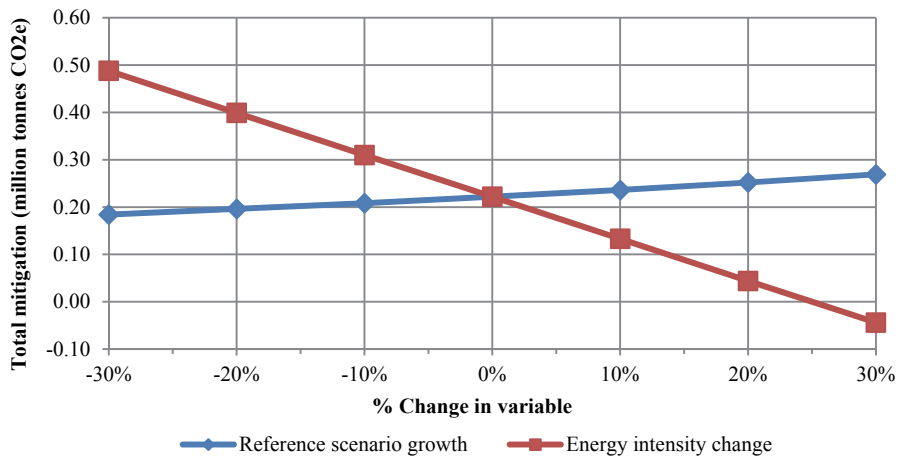


Figure A-37. Scenario 15 (HEV-Tru) sensitivity analysis for mitigation potential (2009-2050).

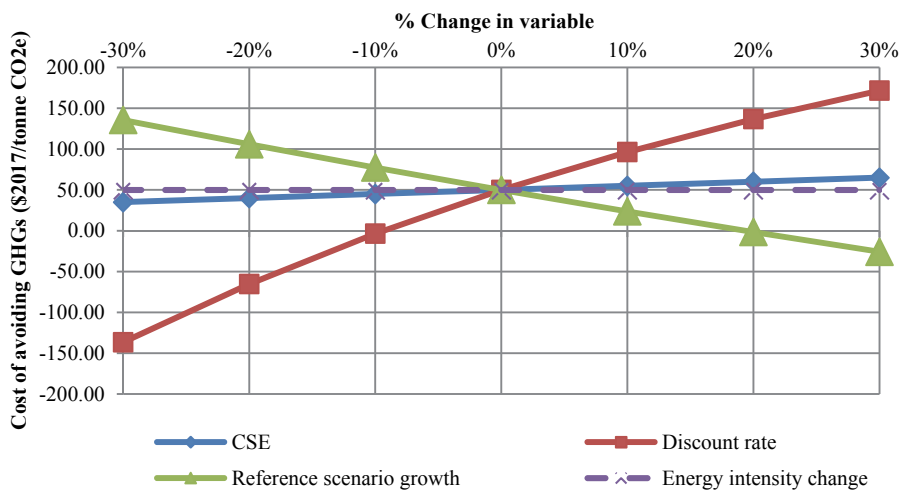


Figure A-38. Scenario 16 (E-Tru) sensitivity analysis for cost of avoiding GHG emissions (2009-2050).

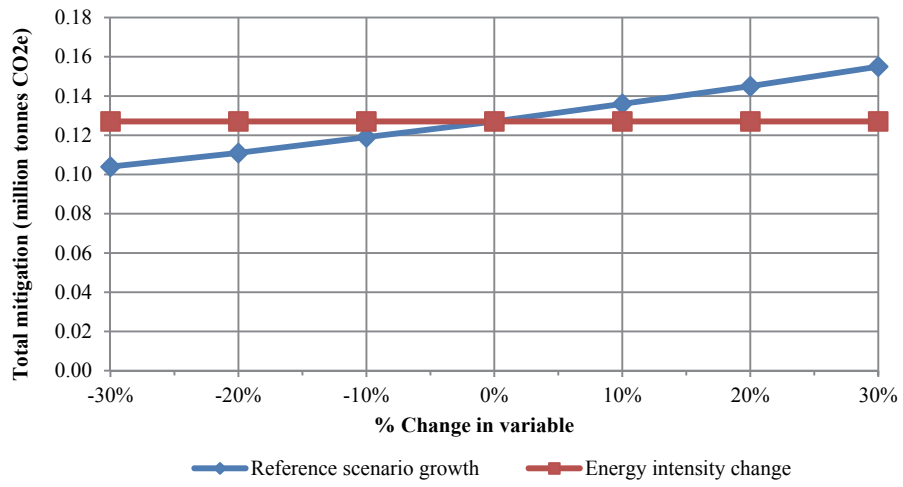


Figure A-39. Scenario 16 (E-Tru) sensitivity analysis for mitigation potential (2009-2050).