Energy Efficiency Improvement Opportunities and Associated Greenhouse Gas Abatement Costs for the Residential Sector

Veena Subramanyam[1], Amit Kumar[*,1], Alireza Talaei[1], Md. Alam Hossain Mondal[1, 2]

[1]Faculty of Engineering, Department of Mechanical Engineering, 10-203 Donadeo Innovation Centre for Engineering, 9211 116 Street NW, Edmonton, Alberta, Canada T6G 1H9

[2]International Food Policy Research Institute (IFPRI), 2033 K Street, NW Washington DC 20006, USA

Abstract

Despite improvements, the residential sector is one of most energy-intensive sectors in the world and is the third largest consumer of energy across Canada, and in Alberta in particular. This study investigates opportunities to improve energy efficiency and reduce greenhouse gas emissions (GHG) in the residential sector. A case study for Alberta is conducted. Energy modelling and scenario analyses are used to project future energy savings and greenhouse gas mitigation potential in the residential sector. Seventeen energy-saving options are identified in different residential subsectors, including space heating and cooling, water heating, appliances, and

[1]*Corresponding author Tel.: +1-780-492-7797.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

lighting. The long-term impacts (i.e., from 2013 to 2050) of these technologies in terms of energy savings and greenhouse gas mitigation potential are assessed using the Long-range Energy Alternative Planning model. For the evaluated options, more than 80% of GHG mitigation is achievable with negative GHG abatement cost. A GHG abatement cost curve is developed to assess the economic performance of various options. The results of the cost curve indicate that efficient lighting, efficient furnaces, and high efficiency appliances are the three areas in which the most GHG mitigation can be achieved at the lowest cost. The results provide invaluable insights to policy makers.

Key words: Energy modeling; residential sector; scenario analysis; energy saving; LEAP.

1. Introduction

In the past few decades, energy consumption has increased in almost every energy subsector worldwide. Of all the sectors, the residential sector is one of the biggest consumers of energy. It is responsible for more than 18% of global energy demand [1] and is the third biggest consumer of energy after the industrial and transportation sectors. In addition, continually increasing GHG emissions from the residential sector makes the sector a large source of GHG emissions globally [2].

Residential sector energy models are generally of two kinds, top-down and bottom-up. In the first, macro-economic factors such as gross domestic product (GDP), household income, energy price, and population growth are used to predict future energy consumption in the sector. In the bottom-up approach, energy consumption in end-use technologies (i.e., those used for heating, cooling, lighting etc.) is assessed and then aggregated to calculate data on households at local, regional and national levels (Figure 1).

(Figure 1)

Top-down models generally use regression analysis and little data and so their applicability in assessing the effectiveness of energy efficiency measures is limited [3]. Top-down models are usually used to conduct high-level policy analyses such as evaluating the impacts of different factors on the penetration of certain technologies [4] or qualitative analyses of promoting energy efficient technologies [5].

Bottom-up models, on the other hand, use a detailed database of energy consumption and allow the user to evaluate the impacts of different technologies on energy consumption and GHG emissions within a system [3]. Bottom-up models have been widely used in residential sector energy modeling. Shimoda et al., for example, developed a bottom-up model to evaluate the impacts of energy efficiency technologies and standards on residential energy consumption in Japan [6]. Farahbakhsh et al. developed the Canadian Residential Energy End-use Model (CREEM) to evaluate the impacts of energy efficiency standards (as opposed to energy efficiency technologies) on residential energy consumption in Canada [7]. In terms of energy saving options, the existing literature considers a wide range of technologies, including efficient water heaters, appliances, air conditioning, and lighting [8, 9], as well as factors such as behavioral changes in promoting energy efficiency measures in the residential sector [10-13]. However, there is limited work that assesses these measures in terms of either associated costs or GHG mitigation potential over medium- and long-term planning horizons.

GHG abatement cost curves are an effective tool used to evaluate energy saving options for emissions reduction. GHG cost curves help prioritize energy efficiency options based on their effectiveness in energy conservation and GHG mitigation potential [14]. GHG abatement cost curves can be developed using both qualitative and quantitative techniques. In the former, the curve is developed based on experts' opinions and in the latter, the results of energy modelling are used [15].

The application of energy models for developing GHG abatement cost curves has both strengths and weaknesses [16-19]. Ackerman et al. developed a model based on cost curves to analyze climate economics [20]. There are a few comprehensive, bottom-up studies that assess GHG mitigation options in the residential sector [21, 22]. Despite the proven effectiveness of cost curves for GHG mitigation assessment in different energy systems' sub-sectors (including the residential sector), there are no studies specific to the residential sector and cold countries like Canada that develop GHG abatement cost curves. Assessments of energy-use reduction potential and GHG mitigation opportunities through various energy efficiency improvement strategies in the residential sector require a comprehensive analysis based on the characteristics of a particular jurisdiction. In this study, a case study was conducted for Alberta.

In Alberta, like the rest of Canada, the residential sector is the third biggest energy consumer [7, 23, 24]. The average residential energy consumption is much higher in Alberta than in other provinces and has shown an increasing trend for several decades.

Specifically, between 1990 and 2011, the overall energy consumption and GHG emissions in Alberta's residential sector increased by 39% and 28%, respectively [24, 25]. Within the sector, energy is used in different sub-sectors, i.e., space heating and cooling (64%), water heating (17%), appliances (14%), and lighting (4%) [24, 26]. The interlinked energy end user characteristics in the residential sector provide a variety of opportunities for energy savings and GHG emissions mitigation though the integration of energy efficient technologies [26, 27], something that is usually achievable over the long term [28]. Scenario analysis techniques are useful for assessing the impacts of long-term energy-saving options on both energy consumption and GHG emissions mitigation. There is little information on residential sector GHG mitigation options and associated costs for the province of Alberta. This study is an effort to fill this gap.

The overall objective of this paper is to conduct a comprehensive assessment and development of GHG abatement cost curves for Alberta residential sector using the Long range Energy Alternatives Planning System (LEAP) model [29, 30]. The specific objectives are to:

- Identify energy savings options in the residential sector
- Assess the energy savings potential for the identified energy saving options using the LEAP model
- Assess the GHG mitigation potential for the identified energy efficiency options using the LEAP model
- Assess the associated GHG mitigation for the identified energy efficiency options and

- Develop a cost curve to assess and prioritize the energy saving options based on both their GHGs mitigation potential and associated cost.

2. Methodology

Based on a comprehensive literature review and identified gaps, applicable residential sector energy-saving options are identified and assessed. The LEAP model is used to assess the long-term impact of each energy-saving option on both energy consumption and GHG emissions in Alberta's residential sector. To this end, a comprehensive database is developed for all the different sub-sectors in the residential sector (discussed in section 2-2). The database is the basis for developing scenarios and assessing the long-term impacts of energy efficiency measures on both overall energy consumption and GHG emissions in the sector (section 2-3). The results of the scenario analysis are used to develop the GHG abatement cost curve. Figure 2 shows the overall structure of this analysis.

(Figure 2)

2.1. The LEAP Model

The LEAP model was developed by the Stockholm Environmental Institute (SEI) in Boston [31]. LEAP is a tool used for long-term system analysis and scenario development [29]. The model uses a bottom-up approach wherein end-use technology-level data are used to develop long-term and high-level scenarios [32, 33]. The effects of the implementation of different energy-saving options and alternate sources of energy on the amount of GHG emissions from the system can be assessed using this model. The model is a best suited for forecasting energy systems in the mid to long term (typically between 20 and 50 years) [34].

LEAP has been widely used for system analysis and energy planning on local, regional, and national levels [34-41]. Areas of application range from the electricity sector [42, 43] to the industrial sector [30, 44], the transportation sector [45-47], and the residential and commercial sectors [48-50]. LEAP can simulate the costs associated with each technology (both capital and operating costs) as well as the external costs of environmental pollutants [34]. It has a built-in technology environmental database (TED), which includes the emission factors for different technologies and different fuels.

The LEAP modeling method is based on building an energy use and supply database and extending it to simulate various long-term energy scenarios. The developed scenarios can be studied further in terms of emissions and costs for a particular region or country

[31]. The model consists of four modules: demand, transformation, resource, and a technology and emissions database. Further details can be found elsewhere [31, 40].

2.2. Data Collection and the Base-Year Demand Tree

The data used in the model range from technology-level energy-intensity data to macroeconomic data such as gross domestic product (GDP), population growth, and fuel price projections. Data are collected from provincial and federal publically available databases and the literature [27, 51-57] and also through consultation with experts.

The detailed demand tree for the residential sector includes all the end-use energy technologies. The residential sector is divided into four categories: single detached homes, single attached homes, apartments, and mobile homes. For each category, various types of end-use energy consumption are considered (i.e., space heating, water heating, space cooling, lighting, and the energy used by appliances) and different end-use technologies, such as various types of furnaces and appliances, and the energy intensity (both current and predicted[2]) of each technology, are considered. Figure 3 shows the detailed hierarchy of the sectors and sub-sectors considered for single detached homes. The same details are considered for single attached homes, apartments, and mobile homes.

[2] Future energy intensities of different technologies are predicted based on the penetration of the technologies (such as Energy Star appliances) and inherent improvement in energy efficiency of those technologies.

(Figure 3)

In order to study the energy supply side, a comprehensive literature review was conducted to collect data on the energy intensity and corresponding environmental impacts of each technology on fuel extraction, processing, and transportation as well as on the electricity generation and distribution sectors.

The comprehensive database on supply and demand sectors made it possible to develop the Sankey diagram for Alberta's residential sector [23]. The Sankey diagram shows energy flow in the sector (from energy resources through energy conversion and transmission to end users) and helps identify the largest energy-consuming subsectors and associated GHG mitigation scenarios.

2.3. Scenario Development

The year 2010 is chosen as the base year for the study. The actual demand side energy intensity of energy technologies and the projection of the energy supply side development are determined based on the data available from Statistics Canada and Natural Resources Canada Office of Energy Efficiency databases and historical energy system evolution between 1990 and 2009 [58]. Base year macro-economic data such as population, GDP, the number of households, and the projections of future growth of these factors are used to develop different scenarios (Table 1) for the time horizons 2013-2030 and 2013-2050.

(Table 1)

2.3.1. Business-as-Usual Scenario

The Business-as-Usual (BAU) scenario is developed based on historical trends in energy consumption and also existing governmental plans in the residential sector. The BAU scenario is developed for the time periods 2013 to 2030 and 2013 to 2050. In developing the BAU scenario, inherent improvement in energy intensity in different technologies is accounted for. More precisely, technology advancement during the time frames and market penetration of efficient technologies are considered. To that end, the EnerGuide and Energy Star equipment guidelines [59] are followed. According to the BAU scenario, by the year 2050 overall energy intensity improvements of 6%, 12%, and 15% (compared to 2010 figures) are anticipated for space heating, water heating, and lighting, respectively [58]. In the same time period, a 20% energy efficiency improvement is expected for home appliances.

Final energy demand in different subsectors, primary energy demand, and the corresponding emissions from the residential sector for the baseline scenario are shown in Tables 2 through 4, respectively.

(Table 2)

(Table 3)

(Table 4)

2.3.2. Energy Efficiency Improvement Scenarios

In the energy efficiency improvement scenarios, it is assumed that different energy efficiency measures will penetrate the energy system during the time periods considered. To account for uncertainties, slow and fast technology penetration rates are considered. Specifically, it is assumed that the efficient technologies will penetrate the system by the years 2030 (fast) and 2050 (slow). Hereafter, the slow and fast penetration scenarios are denoted as the 2050 and 2030 scenarios, respectively.

The efficiency measures considered for scenario development are categorized in four groups: efficient appliances, efficient lighting, efficient water heating technologies, and efficient measures for space heating and cooling. The specific measures considered in each category are summarized in Table 5:

In order to estimate the penetration rates of the different residential sector technologies, the S-shaped sigmoid curve model is used. The S-curve diffusion model illustrates the adoption rate of new technologies as having a) slow penetration (when early adopters start using the technology), b) fast penetration (when the technology is accepted and being used by the majority of consumers), and c) slow penetration again (when the market is saturated) [4, 60-63].

Several assumptions are considered when forecasting residential sector technology diffusion using the S-curve model. It is assumed that the market is saturated with the existing technologies and therefore the penetration rates of the existing technologies will be steady for some time and decline thereafter.

Basic assumptions on the penetration rates of energy efficient technologies and the efficiency improvement rates of the selected technologies are summarized in Table 6. More detailed assumptions on the penetration rates of individual technologies as well as cost, lifetime, and incremental efficiency improvement associated with the adoption of these technologies in the residential sector are shown in Table 7.

(Table 6)

(Table 7)

- **Scenario 1: Efficient Appliances**

In the efficient appliances scenario (APL-HE), it is considered that all of the existing appliances will be replaced by high efficiency technologies during the time periods of the study. Various appliances are considered for this scenario (see Table 5).

The assumptions for appliance penetration rate and efficiency improvement are based on historical trends (for the years 1990-2009) [64] and the authors' previous studies [26, 65], respectively. For both the 2030 and the 2050 scenarios, it is considered that the penetration rate of high efficiency appliances will be high (i.e., more than 90%) at the end of the study period (Table 6). Accordingly, the share of existing appliances remaining will be 10% of the overall market. As shown in the Table, it is considered that on average the efficiency of new appliances would be 20% more than the existing appliances. This assumption is applicable to all major appliances including, refrigerators, freezers, dish washers, dryers, ranges etc. (see Table 5).

- **Scenario 2: Efficient Lighting**

The efficient lighting scenario consists of two sub-scenarios. In both sub-scenarios (LGHT 1 and LGHT 2), it is considered that nearly all existing light bulbs will be replaced by CFL and LED bulbs, respectively.

Currently, incandescent and non-efficient lighting are used for lighting purposes in Alberta and in Canada. The share of incandescent bulbs for lighting is estimated to be 90% and 65% for Alberta and Canada, respectively [66, 67]. The energy intensity of CFL and LED bulbs is 60% and 75-85% (80% is considered in this study), respectively, lower than that of existing light bulbs. In other words, it is considered that the energy intensity of lighting in residential sector has the potential to be improved by 30% by the end of the study period (Table 6). In both the 2030 and 2050 scenarios, the penetration rate of high efficiency lighting is estimated to be high (i.e., more than 90% of the market share) [68].

- **Scenario 3: R-2000 Building Codes for Buildings**

This scenario (BE-R2000) is developed based on R-2000 building code requirements. Implementing code standards is necessary for a building to be eligible for the R-2000 certification. The criteria range from building energy efficiency, improved indoor air quality, and environmental responsibility at the building construction stage.

The energy-saving potential of implementing an R-2000 code is estimated to be limited to 30% and the penetration rate is considered to be no higher than 15%. This is because the R-2000 code would be only mandatory for new buildings and the construction rate of new buildings is assessed to be less than 15%.

- **Scenario 4: Space Heating – Air Source Heat Pumps**

Homes in Alberta are heated by furnaces with low, medium, and high efficiencies. In the space heating-air source heat pumps (SH-ASHP) scenario, it is assumed that existing furnaces would be replaced by air source heat pumps. The technology is used for both space cooling and heating and transfers heat between the indoors and the outdoors.

The coefficient of performance for an AHSP is 2.3, and replacing conventional electric furnaces with an AHSP is expected to result in reduced electricity use in space heating (i.e. the coefficient of performance for modern ASHP is assumed to be 3.3). In terms of penetration rate, due to Alberta's long and cold winters, the penetration of AHSPs for residential heating is expected to be limited [69] to no more than 15% of the overall market during the time periods of this study [68].

- **Scenario 5: Space Heating – Ground Source Heat Pumps**

Similar to the ASHP scenario, the ground source heat pump (GSHP) scenario considers the replacement of existing electric furnaces with GSHP technology to help save energy for both space heating and space cooling. Two sub-scenarios are considered, SH-GSHP (electric) and SH-GSHP (NG), which will reduce consumption of electricity and natural gas, respectively.

Although GSHPs are commercialized, the penetration rate is considered to be minimal. Factors such as low availability and high installation cost make the technology less attractive than existing electric and natural gas furnaces. Although the COP for the GSHP (3.1) is more attractive than existing furnaces, based on the economic competitiveness of GSHPs with other existing and prospective technologies, the market share of GSHPs at the end of the study period is considered to be maximum 15%.

- **Scenario 6: Space Heating – Programmable Thermostats**

Programmable thermostats are state-of-the-art gadgets, the application of which could result in a 6-10% reduction in energy consumption for residential heating compared to regular thermostats [68]. When we developed the space heating-programmable thermostats scenario (SP-PT), we took a conservative approach and considered the ability of this technology to reduce natural gas consumption to be 6%.

Relatively low cost and ease of application [68] make programmable thermostats an attractive option in both existing and new homes. Therefore, a high market share of 90% is considered for PT technology at the end of each study period. In other words, despite the modest energy intensity improvement, the technology has high implementation potential in Alberta's residential sector.

- **Scenario 7: Space Heating – Heat Recovery Ventilators**

Heat recovery ventilators (HRV) are energy efficient ventilation devices that function similar to air heat exchangers. Like other heat recovery systems, HRVs use the energy content of the exhaust air to pre-heat or pre-cool the incoming air.

HRVs will improve the energy efficiency of existing heating systems by 10-14%; 14% is considered in this study [68, 70]. The penetration rate of the technology is expected to be slow, with an assumed market share of 15% at the end of the study periods [68].

- **Scenario 8: Water Heating – High Efficiency Boilers**

The efficiency of the average existing water heating boilers in Alberta is low to medium. In the water heating-high efficiency gas boiler scenario (WH-HE), replacing existing boilers with high efficiency boilers is considered.

High efficiency boilers are 25% more efficient than existing water heating boilers [68]. Due to the relatively long life and high capital cost of high efficiency boilers, their penetration rate is considered to be medium[3]. The market share of high efficiency boilers at the end of study period is thus considered to be 65%.

- **Scenario 9: Water Heating – Low-flow Shower Heads**

The application of low-flow shower heads is expected to result in less water consumption and therefore reduce the need for energy to heat the water. In addition, the need for electricity to pump the water will be reduced. The impacts of the application of this technology on residential energy consumption are assessed in the water-heating-low flow shower heads scenario (WH-LFSH).

A 18% energy saving is achievable through the use of low-flow shower heads [68]. More precisely, implementation of low flow shower head would result in up to 18% reduction in fuel consumption (for water heating) and electricity (for pumping the water). The penetration rate of the technology is considered to be medium during the time period of the study; that is, the technology will have a 65% market share at the end of the study periods.

[3] Itshould be noted that if incentives such as governmental support exist to overcome the high capital cost barrier, the penetration rate of the technology in the market could be faster. However, with the current situation, the midum penetration rate is a more realistic assumption.

- **Scenario 10: Water Heating – Waste Heat Recovery**

The water heating-waste heat recovery (WH-WHR) scenario evaluates the effects of waste-water heat recovery on residential energy consumption. The waste water from showers, dishwashers, clothes washers, etc., contains energy that could be used to preheat the household's input water. Using this energy would reduce the amount of energy needed in the household.

The technology considered in this scenario is a non-regenerative straightforward heat exchanger and the source of energy is the heat recovered from heat pumps, steam condensate lines, and kitchen and laundry drain lines [71]. The achievable energy conservation through the implementation of this technology is between 20% and 50% (25% is considered in modeling), and the penetration rate is expected to be medium, that is, around 65% of the market at the end of the study period.

- **Scenario 11: Water Heating – Condensing Type Water Heaters**

The effect of using condensing-type water heaters in the residential sector is evaluated in the WH-condensing scenario. Condensing heat exchangers can be used in gas-fired water heaters to obtain higher efficiencies. A bigger surface area in this type of heat exchanger makes it possible to condense more water from flue gases, thereby capturing more heat and improving the water heater's efficiency.

The energy efficiency improvement that is achievable by implementing this technology is 15% (combination of the medium and high efficiency of existing technologies is 75-85%) [68] and the penetration rate is estimated to be 65% over the time periods of the study.

- **Scenario 12: Water Heating – Instantaneous Water Heaters**

Instantaneous water heaters do not have storage tanks and water is heated by an electric element or a gas burner as it flows. Tankless technology reduces the energy consumption by reducing standby losses.

The energy-saving potential of using this technology is estimated to be 25% [68, 72] and the market penetration rate would be medium (i.e., 65% by the end of the study period). Similar to scenario 8, high capital cost of replacing the furnaces is the main reason for medium penetration rate of the instantaneous water heater technology.

- **Scenario 13: Building Insulation – Ceiling**

In the building ceiling insulation scenario (BE-ceiling), the energy-saving potential through ceiling insulation is assessed.

High insulation ceilings will result in up to 6% energy saving [68]. The energy saving would be mainly reduction in natural gas consumption. The penetration rate of high insulation ceilings in the market is expected to be higher than the construction rate of the new buildings. This is based on the assumption that every major renovation in existing residential buildings will include high insulation ceilings. Therefore, the market share of the technology at the end of each study period is considered to be 65%, a medium penetration rate.

- **Scenario 14: Building Insulation – Doors**

Installing high insulation doors can save up to 6% of the energy used for both heating and cooling [68]. However, due to the cold climatic condition and low demand for air conditioning during summer time in Alberta, it is expected that the saving would be mainly in form of reduction for the heat demand during winter time. Currently, the share of high insulation doors in Alberta's residential sector is 5% [68]. The market share of these doors is expected to be 65%, in the BE-Doors scenario, a medium penetration rate.

- **Scenario 15: Building Insulation – Walls**

The impact of insulated building walls on a building's energy consumption is considered in the BE-walls scenario. Installing wall insulation will improve the building envelope with a maximum achievable energy-saving potential of 33% [68, 73]. As for Scenarios 13 and 14, we assume that the penetration rate of high insulated walls will be medium, that is, it will have a 65% market share by the end of the study period.

- **Scenario 16: Building Insulation – Windows**

High insulated windows are expected to result in a maximum energy saving of 6% [68, 73]. In order to assess the overall impacts of installing high insulation windows in the residential sector, a medium penetration rate is considered in the BE-windows scenario, which will result in an overall market share of 65% at the end of the study period.

- **Scenario 17: Space Heating – High Efficiency Furnaces**

The annual fuel use efficiency (AFUS) of existing furnaces in Alberta ranges from 62% for normal efficiency furnaces to 82% and 92% for medium and high efficiency furnaces, respectively. Currently, most residential buildings use either normal or medium efficiency furnaces along with electric and oil furnaces. Ultra-high efficiency furnaces (with an AFUE of 94%) are in the initial stages of penetration in Alberta's residential sector. On average, the achievable efficiency improvement from installing high efficiency furnaces is considered to be 15% and the overall share of the technology is considered to reach 65% at the end of the time period of the study.

2.3.3. Cost and GHG Mitigation Assessment

Different costs including capital, operation and maintenance, and technology development costs are considered in the LEAP model [38]. Including energy technology costs in the LEAP model makes it possible to compare the costs associated with implementing each energy-saving (GHG mitigation) option [38]. The results of the LEAP model provide first-hand information on GHG mitigation costs (i.e., $ per tonne of CO_2 abatement), which needs detailed analysis to evaluate the economic viability of the options.

In this study, the BAU scenario is used as the base for comparison, and the cost of GHG mitigation is evaluated by comparing the cost of each energy efficiency scenario with the BAU scenario. This approach makes it possible to assess the incremental cost of implementing each scenario over the time periods of the study. In order to evaluate the comparative cost efficiency of each mitigation option, the cost of each mitigation option is compared with the baseline scenario on the basis of dollar per tonne of CO_2 abatement ($/t$CO_2$). This comparison provides the grounds for developing the GHG abatement cost curve.

In order to develop the GHG abatement cost curve, the costs associated with implementing each scenario (both the baseline and the various mitigation scenarios) are calculated over the time periods of the study. The costs are then harmonized in the form of net present values (NPV). In order to calculate the NPV, an interest rate of 5% is considered. The projection of fuel cost (as a part of the operation cost of each technology) is presented in Table 8.

(Table 8)

As shown in Table 7, various lifetimes are considered for each technology to account for replacement (i.e., capital cost). Combining these two steps (fuel/technology cost and the useful time life of technology) makes it possible to calculate the incremental cost of each energy-saving scenario over the study horizons. The NPV of each option is then divided by its incremental GHG mitigation option in order to conduct a comparative cost-benefit analysis of different options. The cost curve represents the estimate of the incremental abatement cost ($/tonnes of CO_2 abatement) for mitigating a specified amount of GHG emissions in a given period. The cost of saved energy (CSE) is expressed as $/MWh (for electricity) and ($/PJ for thermal energy).

3. Results

Comparing the energy efficiency scenarios we developed with the BAU scenario makes it possible to assess the energy-savings options in the residential sector. Specifically, we assessed the effects of each option in terms of energy saving and GHG mitigation potential as well as the cost of implementing each option over the time period of the study.

As discussed in Section 2-3, we developed 34 different energy efficiency improvement scenarios (17 for each time period of study) ranging from using more energy efficient appliances to improving building insulation. We calculated the energy saving potential and associated GHG emissions reduction. The results are summarized in Table 9.

(Table 9)

As shown in the table, the potential for energy saving varies considerably among different technologies. In the 2030 penetration scenario, for example, the cumulative energy saving potential is less than 10 PJ in some energy efficiency improvement options (e.g., application of air source heat pump) and more than 100 PJ in others (e.g., high efficiency furnaces and building envelope-walls). Cumulative GHG mitigation potential varies from less than 1 to 10 MT CO_{2eq}.

In the 2030 scenario, building envelope-walls and high efficiency furnaces are identified as the biggest energy saving measures, with savings potentials of 138 and 105 PJ, respectively. Alternative water heating technologies such as condensing and instantaneous water heaters are also expected to reduce energy consumption by more than 70 PJ compared to the baseline scenario. Results of the 2050 scenario suggest cumulative energy savings potential of high efficiency furnaces and building envelope-walls will remain the top energy saving measures, with savings potentials of 250 and 228 PJ, respectively. The third biggest energy savings option is in high efficiency lighting, which is expected shows savings of more than 2.8 times the 2030 scenario.

In terms of GHG mitigation, for both the 2030 and 2050 scenarios, lighting offers the biggest GHGs mitigation potential with up to 10 and 26 million tonnes of GHG mitigation by 2030 and 2050, respectively. In the 2030 scenario, building envelope-walls and high efficiency furnaces are the second and third biggest GHG mitigation options with savings potentials of 8 and 6 $MTCO_{2eq,}$ respectively; this potential will increase to 13 and 14 MT CO_{2eq}, respectively, making high efficiency furnaces the second biggest GHG mitigation option by 2050. While the market share of these technologies will be similar in both the 2030 and the 2050 scenarios, the energy efficiency improvement of the technologies and the overall energy consumption of the technologies are different, which explains the differences in the results.

The results also show that the best energy saving options are not necessarily the best GHG mitigation measures. More precisely, while high efficiency lightening offers the biggest GHG mitigation potential, the energy savings achievable through implementing the measure is medium (compared to other technologies). On the other hand, improving the “building envelope-walls” results in both considerable energy savings and GHG emissions reduction. This is due to different emissions factors associated with different energy carriers and technologies.

In order to evaluate the costs associated with implementing energy saving technologies, as discussed in Sections 2.3.3, both capital investment and operating cost are considered. The results suggest that while the incremental costs of technologies such as "building envelope-doors" could be as high as $ 1.7 billion, the overall savings of technologies such as high efficiency lighting will exceed the expenses, potentially saving up to $0.36 billion (in the 2030 scenario). In terms of incremental cost of implementation, different building envelope options (walls, doors, ceilings, and windows) as well as programmable thermostats have the biggest incremental costs in both the 2030 and the 2050 scenarios. The options with the lowest incremental costs are high efficiency furnaces for space heating and high efficiency water boilers. For both the 2030 and the 2050 scenarios, the ultimate penetration potential and the energy saving potential of different energy saving measures are considered to be comparable. In other words, the annual penetration rate differs between the time periods 2010-2030 and 2010-2030. This, together with technology lifetimes (ranging from more than one year for lighting to 35 years for building envelope), has resulted in differences in the cost of saved carbon in the two scenarios, even for similar technologies (Table 10).

(Table 10)

4. Discussion and Implication for Policy

GHG abatement cost curves were developed with the 2030 and 2050 study results to evaluate the effectiveness of different options for mitigating GHG emissions and the economic feasibility of each scenario (see Figures 4 and 5). The figures show the potential for GHG emission reduction and the costs of implementing energy-saving options compared to the BAU scenario. More precisely, on the

GHG abatement cost curve, the horizontal axis shows the cumulative GHG mitigation potential over the time periods of the study and the vertical axis represents the cost per unit of emissions reduction (e.g., \$/tonne CO_2 reduction). The reported cost is the net present value of all costs associated with the mitigation technology, including capital costs and operation and maintenance costs (reported in 2010 dollars). An interest rate of 5% is considered for the NPV analysis. In the GHG abatement cost curve, the cheapest emissions mitigation option is on the left and the most expensive is on the right.

(Figure 4)

(Figure 5)

For the 2050 scenario, more than 80% of the mitigation potential is achievable with negative cost. Negative cost means that the NPV of the benefits gained from implementing this technology is higher than the implementation costs (both capital and operating and maintenance costs). For most of the options considered in this study, the cost saving results in lower fuel costs, as the efficient technologies will consume less energy than the existing ones. For the negative NPV options, the cost reduction from fuel savings is high enough to cover the higher capital cost associated with the application of the high efficiency measures.

As the GHG abatement cost curve shows, replacing an existing thermostat with a programmable one is the least costly of all the options considered. However, its mitigation potential is low; it is less than 2% of the overall achievable mitigation from implementing all the efficiency options. Efficient lighting (i.e., the use CFL and LED) shows the biggest potential of all the GHG mitigation options (about 27% overall mitigation potential). With the potential to mitigate 46 MT GHG emissions ($CO2_{eq}$), high efficiency lighting will reduce emissions with negative cost. All the energy-saving options for water heating can be implemented with negative costs and offer a mitigation potential of 33 million tonnes of CO_2 equivalent by 2050.

The results also suggest that energy savings in the space heating scenarios offer considerable potential for GHG emissions reduction. Except for insulated doors, HRV, and high efficiency furnaces (with an overall GHG mitigation potential of 23 MT), other building envelope mitigation options will result in some positive costs. This means that the sum of capital cost and operation and maintenance cost exceeds any cost savings achievable by implementing these options. If the mitigation cost is the major criterion for choosing the mitigation option, none of the building envelope options should be considered as high priority options.

In the 2030 scenario, more than 72% of the overall GHG mitigation could be achieved with negative cost[4]. Like the 2050 scenario, lighting has a major role in GHG emissions reduction and accounts for 24% of the overall reduction potential. Energy-saving options for space heating and cooling have high mitigation potential and are also economically attractive, like high efficiency furnaces and well insulated doors.

[4] It needs to be noted that not all the scenarios can be implemented simultaneously.

The results of the study are expected to provide insightful input to policy makers. Application of scenario analysis has provided the opportunity to account for areas of uncertainty. While the analysis of energy saving options in terms of potential energy efficiency improvement and its associated costs are transferable to other jurisdiction within Canada and beyond, the calculated GHG mitigation potential is specific to Alberta. More precisely, among other factors, the two determining assumptions for the modeling were penetration rate of energy efficient technologies and the emission factors of the fuel combustion.

The penetration rate is calculated considering the current share of energy efficiency technologies in the market and the maximum adoption potential for the technologies. These factors vary in different jurisdictions. For the case of Alberta, different penetration patterns are considered for various technologies (Table 6).

5. Conclusion

This study investigated long-term energy consumption and energy-saving potential in the residential sector for a region with a cold climate. Using a bottom-up approach, technology-level energy consumption in different residential applications was used to analyze energy flow in the sector and to identify the major energy consumers. Space cooling and heating, water heating, appliances, and lighting are the major energy consumers in the residential sector. A case study for Alberta, a province in Canada, was done.

Different energy-saving (GHG mitigation) options that can help reduce residential energy consumption in the long term were identified. The impacts of each option over time horizons up to 2030 and 2050 were evaluated using the Long-term Energy Alternative Planning model. The GHG emissions associated with each scenario were calculated using the LEAP model for Alberta. The model results are presented in a GHG abatement cost curve that shows the mitigation potential of each option (compared to the business-as-usual scenario) and the relative cost of implementing each option.

The results suggest that for both the 2030 and the 2050 scenarios, implementing several of the GHG reduction measures would have negative cost. Results from both scenarios indicate that the implementation of high efficiency lighting, along with efficient furnaces and appliances, is expected to play a major role in mitigating GHG emissions in the residential sector. The results of this study could be used by the decision makers to formulate policies and investment decisions.

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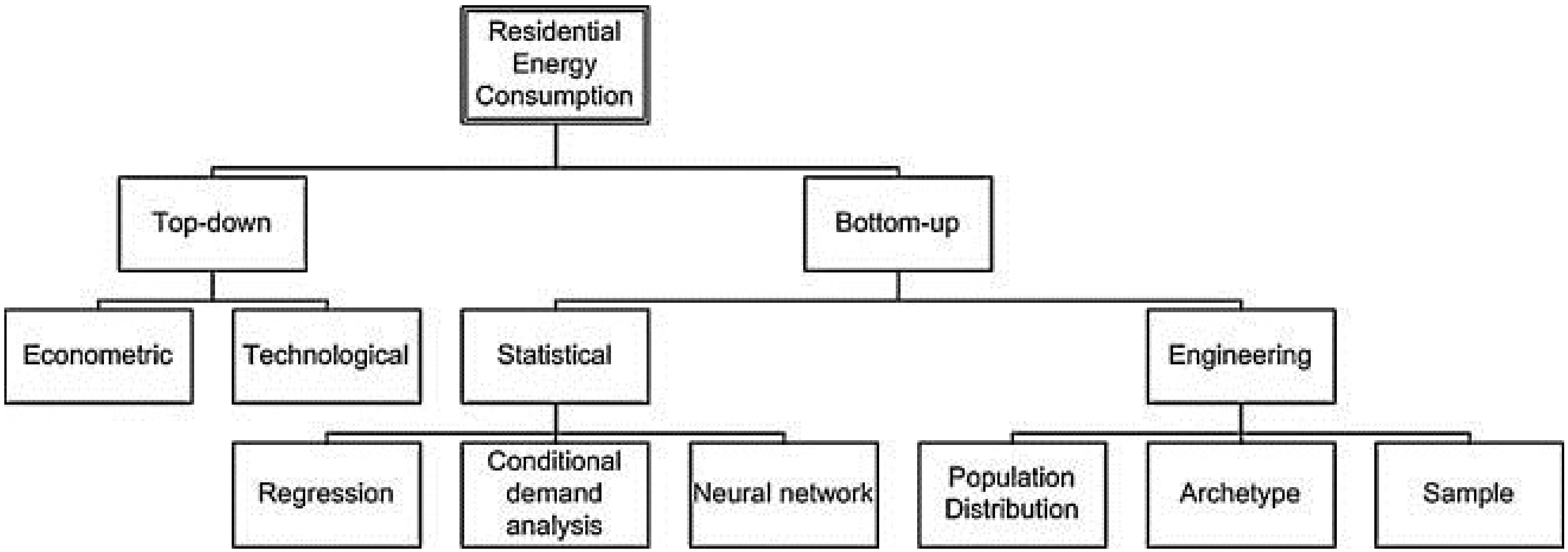

Figure 1: Top-down vs. bottom-up approach for residential energy modelling Adapted from [3] with the permission of Elsevier Publishing Solutions (license number: 3855471202292).

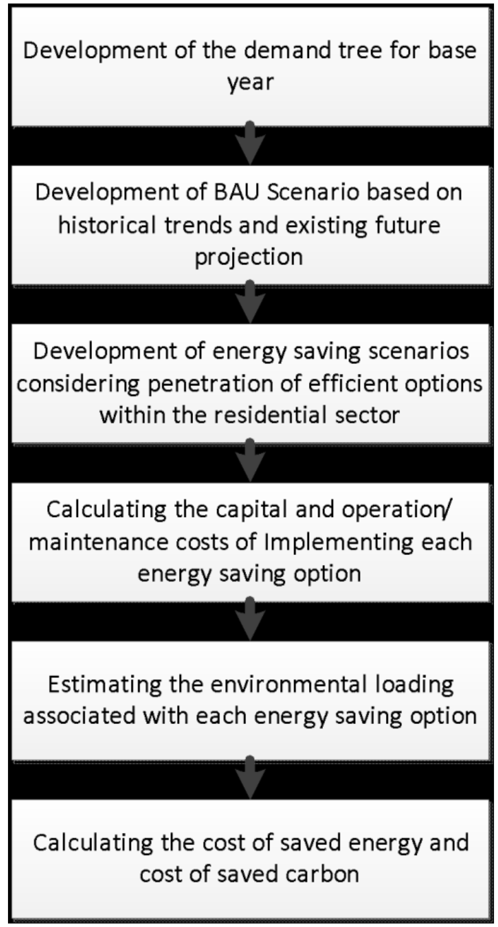

Figure 2: Method for the development of the GHG mitigation cost curve

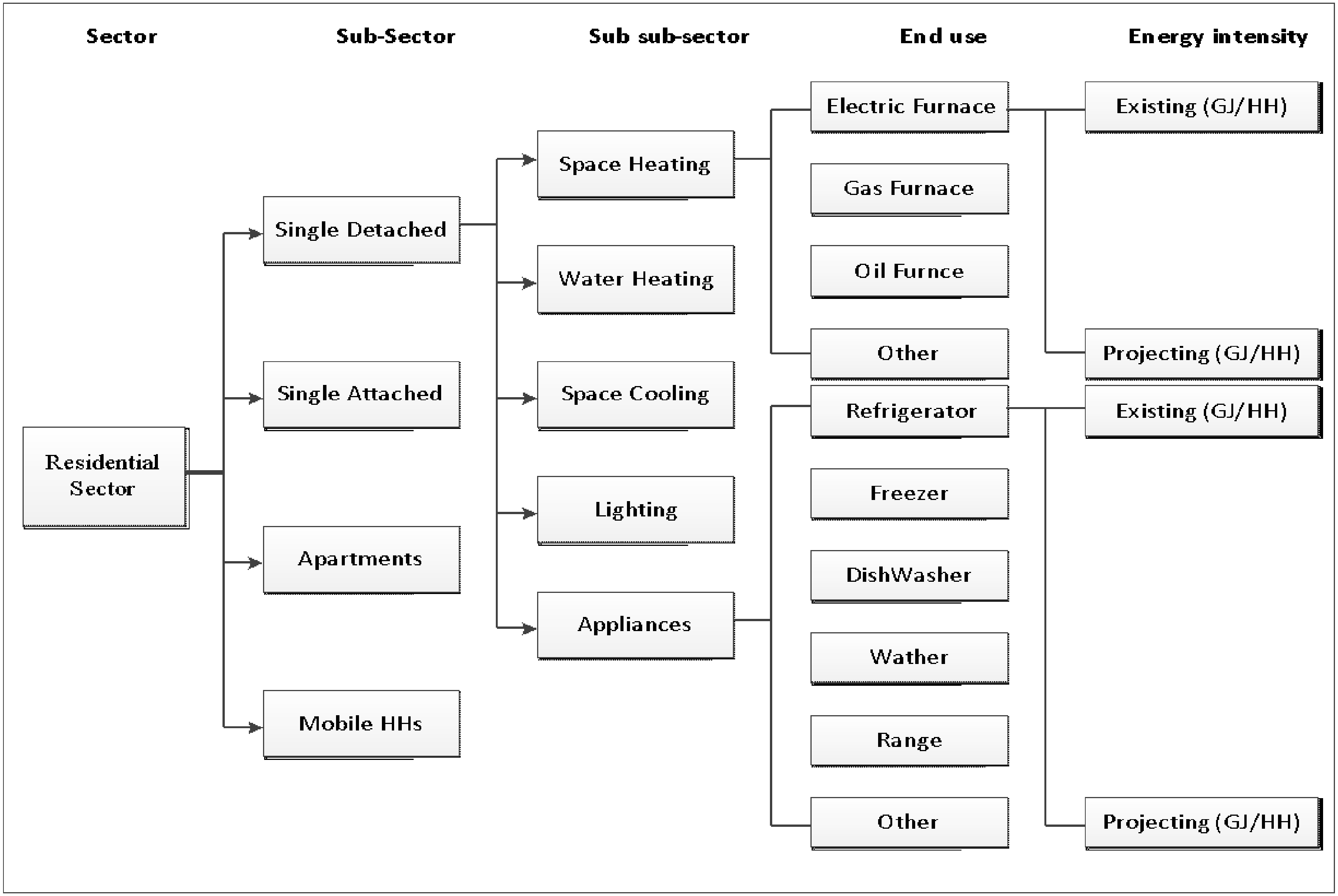

Figure 3: Demand tree for Alberta's residential sector

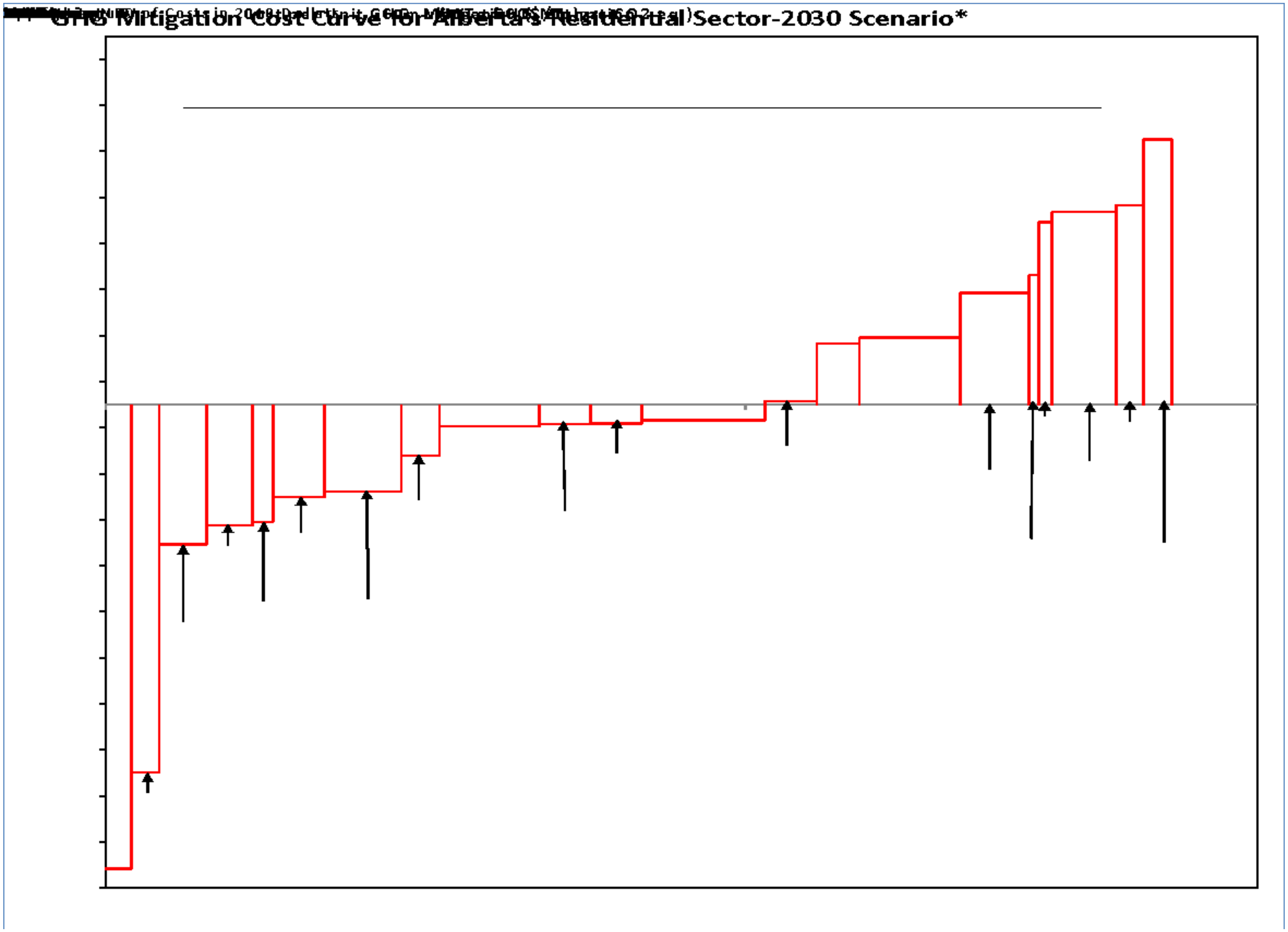

Figure 4: GHG mitigation cost curve for Alberta's residential sector, 2030 scenario (2013-2030)

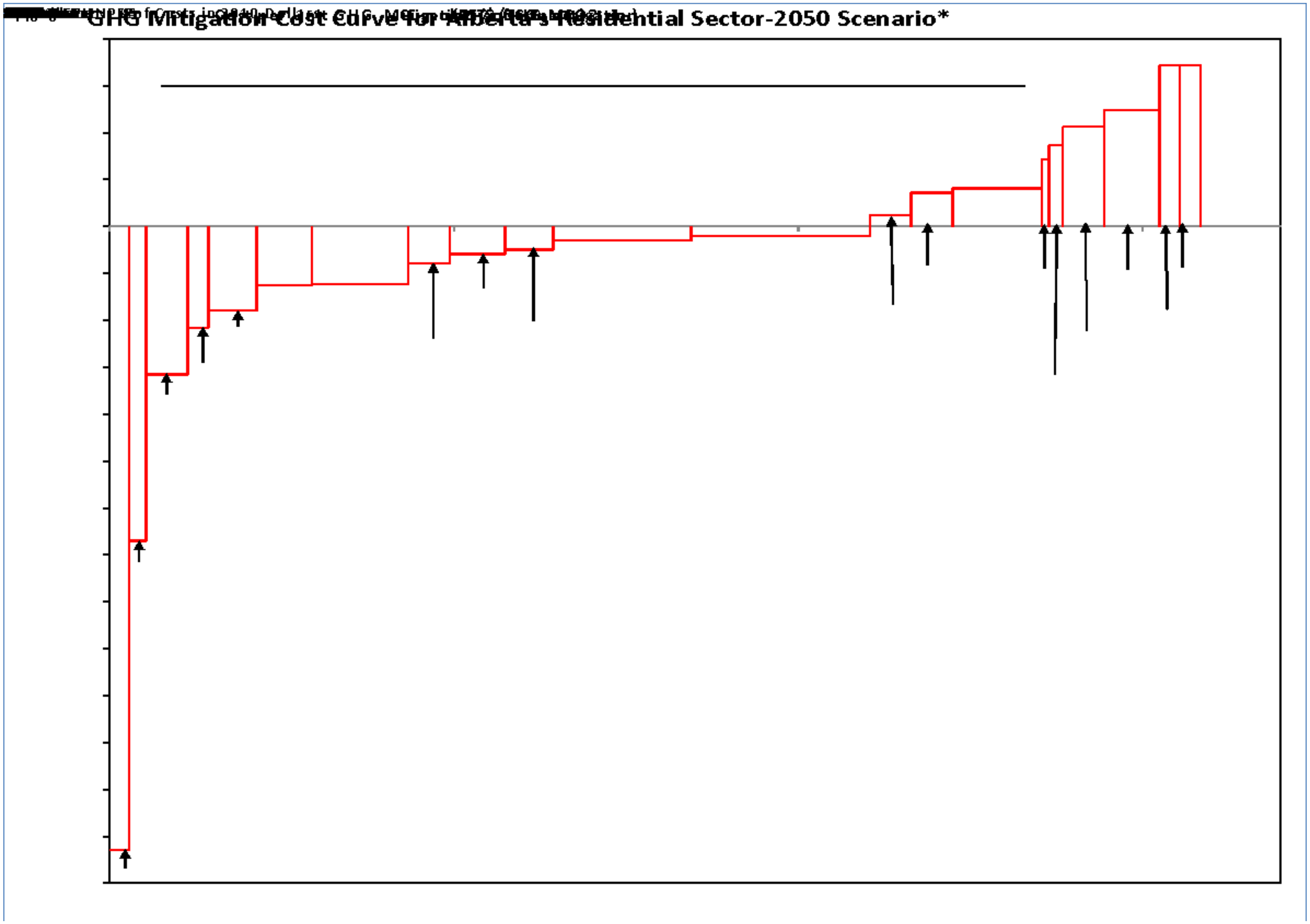

Figure 5: GHG mitigation cost curve for Alberta's residential sector, 2050 scenario (2013-2050)

Table 1: Key parameters in the reference scenario from 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (000)	3413	3607	3811	4028	4256	4498	4753	5023	5308
GDP (billion $)	151	175	202	235	272	315	365	424	491
Household (000)	1331	1407	1486	1571	1660	1754	1854	1960	2070

Table 2: Final energy demand in household sub-sectors from 2010-2050 (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Single detached	143	153	165	176	189	204	219	236	254
Single attached	15	16	18	19	20	22	24	25	27
Apartments	21	23	25	26	28	30	33	35	38
Mobile homes	8	9	9	10	11	12	13	13	15
Household (total)	187	201	216	232	249	268	288	310	334

Table 3: Primary energy demand in the reference scenario from 2010-2050 (PJ)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Biomass	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8
Electricity	25.2	26.9	28.8	30.7	32.9	35.1	37.6	40.2	43.0
Natural gas	160.7	172.6	185.4	199.1	213.8	230.3	248.0	267.1	287.7
Oil products	1.3	1.4	1.5	1.6	1.8	1.9	2.1	2.2	2.4

Table 4: Projected GHG emissions for residential sub-sectors in the reference scenario (MT)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Single detached	7.02	7.54	8.09	8.68	9.32	10.04	10.83	11.67	12.58
Single attached	0.64	0.69	0.74	0.8	0.86	0.92	0.99	1.06	1.14
Apartments	1.04	1.12	1.21	1.3	1.4	1.5	1.6	1.72	1.84
Mobile homes	0.4	0.43	0.46	0.5	0.53	0.58	0.62	0.67	0.72
Total	9.1	9.77	10.49	11.27	12.1	13.03	14.04	15.12	16.28

Table 5: Energy efficiency options for scenario development

Energy efficiency category	Energy efficiency option
Space heating and cooling	High efficiency furnaces
	Air conditioners
	Air source heat pumps (ASHP)
	Ground source heat pumps (GSHP)
	Ventilation motors in residential furnaces
	Heat recovery and ventilation systems (HRV)
Water heating	High efficiency water heaters
	Condensing water heaters
	Thankless or instantaneous water heaters
	Waste heat recovery
	Low flow shower heads
Lighting	Improved energy efficiency
	Compact florescent lamps (CFL)
	Light emitting diodes (LED)
Appliances[5]	High efficiency refrigerators
	High efficiency freezers

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	High efficiency cloth and dishwashers
	High efficiency dryers
	High efficiency ranges
	High efficiency microwaves
	High efficiency televisions
	High efficiency cable boxes
	High efficiency stereo systems
	Desktops and home computers

Table 6: Summary of energy efficiency improvement scenarios

No.	Scenario	Description	EI imp. (%)[6]	Pen. Rate (%)[7]
1	APL-HE	Penetration of high efficiency appliances	20	90
2	LIGH 1 &2	Replacing current lighting technologies with CFL (LGHT 1) and LED (LGHT2)	30	90
3	BE-R2000	Implementing R-2000 standards for residential buildings	30	15
4	SH-ASHP	Replacing low, medium and high efficiency furnaces with ASHP technology	COP 3.3	15
5	SH-GSHP	Replacing low, medium and high efficiency furnaces with GSHP technology	COP 3.1	15
6	SH-Thermostat	Replacing regular thermostats with Programmable thermostats	6	90
7	SH-HRV	Installation of Heat Recovery Ventilation system to preheat or precool the incoming air	14	15
8	WH-HE Boiler	Application of high efficiency boilers for water heating	25	65
9	WH-Low Flow SH	Using low flow shower head to reduce water consumption and therefore energy consumption	18	65
10	WH-WHR	Use the energy content of waste water to preheat the incoming water	25	65
11	WH-Condensing	Application of condensing type water heaters instead of conventional water heater	15	65
12	WH-Instantaneous	Using tankless/instantaneous water heater to heat the water on demand	25	65
13	BE-Ceiling	Using insulation to avoid heat loss from ceiling	6	65
14	BE-Doors	Using insulation to avoid heat loss from doors	5	65
15	BE-Walls	Using insulation to avoid heat loss from walls	33	65
16	BE-Windows	Using insulation to avoid heat loss from windows	6	65
17	SH-HE Furnaces	Replacing existing furnaces with high efficiency furnaces	15	65

[6] Energy efficiency improvement (considered in the LEAP model)
[7] Market share by the end of the study period

Table 7: Input data for all developed energy efficiency improvement scenarios

Scenarios	Existing Stock			Efficient Stock			Incremental		
Technology	Description	Eff. (%)	Cost/ unit ($)	Description	Eff. (%)	Cost/unit ($)	Eff. (%)	Cost/unit ($)	Life
Efficient appliances	combination of appliances	-	450-800	Combination of appliances	Varies	1000	EI gain 20% for new appliances	Range (800-1200)	Based on appl
Lighting LGHT1/ GGHT2	Existing stock > 80% incandescent bulbs	15-20%	$ 0.5 /bulb inc. & $ 6 /bulb CFL	CFL/LED bulbs	75%/ 85%	7/ 28	65%/75% improvement in efficiency	Difference of new and weighted average of existing	10000/ 25000 hrs
Building envelope and standard	New houses will have R2000	NA	200000	New house with R2000	NA	215000	EI gain by 30%	15,000	35 yrs
Air source heat pump	Electric furnace to be replaced by ASHP	100	2,000	COP for -8°C is 2.3	230	6000	130	4000	25 yrs
GSHP heat for electric/ NG furnace	Electric/NG furnace to be replaced by GSHP	100/ 85	2,000/ 5000	COP considered is 3-3.8/4 for Alberta	300/ 400	10000/ 25000	200/315	8000/ 20000	25 yrs
Programmable thermostat	Default penetration assumed	NA	-	penetration up to 90%	NA	-	EI reduction by 6%	100	10 yrs
Heat recovery ventilator	Efficient stock will have HRV	NA	-	Considered energy/m^3 & incremental costs for detached houses	NA	-	EI improvement by 14%	600	20
Water heating - gas boiler	75-80%	-	-	For a typical detached house	-	-	EI gain 25%	500	18
Low-flow shower head	Medium to high eff. stock (75-	-	-	-	-	-	EI gain 18%	50	20

	85%)								
Waste Heat Recovery	75-80%	-	-	For a typical detached house	-	-	EI gain 26%	500	18
WH – Condensing	Combination-medium/high eff. (75-85%)			Based on a typical water heating load			EI gain 30%	2500	18
WH – Instantaneous	Medium and high efficiency (75-85%)	-	-	For a typical house using over 41 gallons/day	-	-	EI gain 25%	750	18
Building envelope – ceiling	Existing and new stock have efficiency improvement	NA	-	Envelope ceiling for a detached house	NA	-	NG savings 6%	1200	35
Building envelope – doors	Same as above	NA	-	High-efficiency doors considered	NA	-	EI gain calculated 5%	500	35
Building envelope – walls	Same as above	NA	-	Energy and cost for 1500 ft^2 of basement & main wall	NA	-	EI gain 33%	3750	35
Building envelope – windows	Same as above	NA	-	Weatherization ($1200/ detached house)	NA	-	EI improve. estimated to be 6%	1200	35
High efficiency furnace	Existing with high, medium and low eff. furnaces (H=90, M=80, L=62)	80	3,000	High eff.> 90% furnace to penetrate up to 65%	95	5000	15	2000	18

Table 8: Forecasted fuel prices used to calculate the cost of saved energy (CME, 2012; NEB, 2011)

Fuel prices	2010-2020	2020-2030	2030-2040	2040-2050
Natural gas ($/GJ)	7.5	8.5	9.5	11
Electricity ($/KWh)	0.11	0.15	0.20	0.27
Gasoline ($/GJ)/$/liter)	33/1.5	36.3/1.6	40/1.7	43.9/1.8
Ethanol ($/GJ)/$/liter)	41.8/1.03	41.8/1.03	39.7/0.95	37.7/0.9
Diesel	29	30.45	31.97	33.6
Biodiesel	31.6	31.6	30.0	28.5
Compressed natural gas (CNG)	23.3	24.42	25.64	26.9
Liquefied natural gas (LNG)	10	10.5	11.0	11.6

Table 9: Summary results of energy saving, GHG emissions, and related costs for the 2030 and 2050 cases

	Scenario results for 2030 case				Scenario results for 2050 case			
All energy-efficiency scenarios	**Energy reduction Cum. (PJ)**	**GHG mitigation Cum. (MT)**	**Increm. NPV costs (billion $)**	**Abate. cost ($ per ton. CO_2)**	**Energy reduction Cum. (PJ)**	**GHG Mitigation Cum. (MT)**	**Increm. NPV costs (billion $)**	**Abate. cost ($ per ton. CO_2)**
Appliances (APPL)	-27.0	-3.9	0.77	-201	-55.0	-8.0	- 1.0	-126
Light - Efficient lighting (LGHT1/LGHT2)	-45/-56	-8/-10	-0.36/-0.33	-47/-34	-124/-156	-20/-26	-0.6/-0.5	-30/-21
Building envelope - R2000	-58.3	-3.3	0.4	133	-100.0	-5.6	0.4	72
Space heating - air source heat pump (ASHP)	-4.3	-0.8	0.24	281	-7.7	-1.3	0.18	144
SH ground source heat pump - Replacing electric/NG – GSHP(E) and GSHP (NG)	-5.8/ 200	-1.0/ 5.0	0.4/1.3	396/242	-10.4/ 235	-1.7/ 5.6	0.3/1.19	173/212
SH – programmable central thermostat (Thermostat)	-42.1	-2.4	2.4	1008	-50.5	-2.9	3.7	-1300
SH - high-efficiency HRV	-29.1	-1.7	0.42	255	-47.4	-2.7	0.5	216
Water heating – high-efficiency boiler (HE-Boiler)	-62.6	-3.5	-0.92	-262	-108.1	-6.1	-1.9	-318
Water heating – low-flow shower head (LFSH)	-56.6	-3.7	- 1.1	-303	-94.9	-6.5	- 1.1	-179
Water heating – waste heat recovery (WHR WH)	-47.6	-2.7	- 0.29	-110	-100.2	-5.6	- 0.44	-78
Water heating – condensing WH (Cond WH)	-76.0	-4.3	- 0.17	-41	-137.3	-7.7	- 0.45	-59
Water heating – instantaneous WH (Instant WH)	-73.9	-4.2	-0.18	-44	-132.6	-7.4	-0.3	-59
Building envelope – ceiling (Ceilings)	-37.1	-2.1	0.9	433	-44.4	-2.5	0.8	343
Building envelope - doors (Doors)	-37.9	-2.2	1.7	-799	-44.4	-2.5	1.6	-670
Building envelope – walls (Walls)	-137.8	-7.9	1.1	146	-227.8	-12.8	1.0	81
Building envelope – windows (Windows)	-37.9	-2.2	1.2	576	-44.4	-2.5	0.85	343
Residential space heating – HE furnace (HE Furnace)	-105.0	-6.0	-1.1	-189	-250.7	-14.1	-1.7	-122

Table 10: Estimated costs of saved energy for all energy efficiency improvement scenarios ($/GJ)

Scenarios/Cost of saved energy	2010-2020	2020-2030	2030-2040	2040- 2050
Scenario 1: APL – HE Appliance	-0.02	-0.05	-0.10	-0.11
Scenario 2: LHT – CFL/LED	-0.06/-0.07	-0.09/-0.13	-0.13/-0.18	-0.20/-0.25
Scenario 3: BE - R2000	7.31	6.31	5.3	3.81
Scenario 4: SH - ASHP	0.47	0.43	0.38	0.32
Scenario 5: SH - GSHP – Gas/Electricity	8.84/0.75	7.98/0.71	7.64/0.66	7.6/0.6
Scenario 6: SH - Thermostat	-4.0	-5.0	-6.0	-9.25
Scenario 7: SH – HRV	-4.37	-5.89	-7.41	-8.91
Scenario 8: WH – HE Gas boiler	-1.59	-2.59	-2.62	-2.72
Scenario 9: WH – Low-flow SH	-6.81	-8.26	-9.22	-10.70
Scenario 10: WH – WHR	-1.53	-2.44	-3.33	-4.60
Scenario 11: WH – Condensing WH	-1.03	-2.03	-3.03	-4.53
Scenario 12: WH – Instantaneous WH	-0.57	-1.46	-4.46	-3.84
Scenario 13: BE – ceiling	3.61	2.6	1.61	0.11
Scenario 14: BE – doors	-2.87	-3.87	-4.87	-6.37
Scenario 15: BE – walls	2.92	1.92	0.92	0.58
Scenario 16: BE – windows	3.61	2.61	1.6	0.11
Scenario 17: SH – HE Furnace	-2.31	-3.31	-4.31	-5.81