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An Environmental Life Cycle Assessment

OF A BIO SPRAY POLYURETHANE FOAM INSULATION IN THE CONTEXT OF ALBERTA, CANADA

First draft final report

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Table of Contents

Executive Summary

In a long, frigid winter climate such as Alberta's, building insulation is an important material that can aid in reducing space heating energy demand. As the National Energy Code for Buildings of Canada continues to require higher minimum thermal resistance (R-) values for envelope insulation, spray polyurethane foam (SPF) is an attractive solution that can replace the more conventional yet lesser quality fiber glass batt (FGB) insulation. This is because SPF can offer approximately double the R-value per unit thickness while simultaneously providing a considerably lower rate of natural air infiltration. In addition, SPF offers better sound attenuation and even contributes additional structural stability to the wall allowing for less framing material. Despite these benefits, the majority of SPF products on the market today are almost entirely derived from fossil fuel intense materials, making the initial insulation investment questionable in terms of environmental impact. To mitigate these concerns, 1782815 Alberta Ltd. has partnered with Green Analytics and the Lipids Chemistry Group at the University of Alberta to develop a novel bio-based SPF product where local canola oil feedstock can be utilized to produce a bio-polyol product that can significantly reduce the climate change impact of SPF insulation from a life-cycle perspective.

In Stage 1 of this analysis, an environmental life cycle assessment (LCA) of a novel bio-SPF product is undertaken where a total climate change impact of 4.59 kg CO_2eq per functional unit (*f.u.*) was calculated—the functional unit being equal to insulating a 1 m^2 area of envelope surface at an R_{SI} value of 1 (m^2-°C/W) for a 60-year time period. The main results indicate that potentially substantial greenhouse gas (GHG) reductions are possible. When the blowing agent is disregarded, the results indicate that approximately 1.0 kg CO_2eq/*f.u.* can be reduced when the bio-polyol replaces the conventional fossil based polyol, and this is largely due to the benefits of utilizing local no-to-low tillage canola-derived oil for the production of polyol, which makes up roughly 40% of the final SPF insulation product. If this bio-SPF can also be successfully commercialized with the use of a methyl formate blowing agent which has a global warming potential (GWP) of zero kg CO_2eq/kg methyl formate, thereby replacing the conventional HFC-245fa blowing agent with a GWP of 1030 kg CO_2eq/kg HFC-245fa, GHG reductions can be significantly greater at approximately 26 kg CO_2eq/*f.u.*

In Stage 2 of this analysis, the operational building performance in terms of energy demand is determined when the SPF insulation is assumed to replace the more conventional FGB insulation. Space heating savings in Alberta are found to range from 25 to 48% for the apartment archetype and from 10 to 27% for the detached house archetype simulated in this study. The associated GHG reductions when natural gas space heating is assumed range from 11 to 27 kg CO_2eq per m^2 gross floor space per year depending on building type and year round climate (temperature) conditions. Since the bio-SPF product is found to have a higher carbon footprint than the FGB insulation (4.59 kg CO_2eq/*f.u.* versus 3.53 kg CO_2eq/*f.u.*), a GHG payback period of less than one year is required before climate cooling benefits relative to the FGB baseline is possible. If methyl formate (or a similar zero GWP blowing agent) cannot be realized in this novel bio-SPF product and HFC-245fa is relied upon, then the GHG payback period increases to 7 to 9 years for the apartment building and 15 to 20 years for the detached house. Therefore, in terms of climate change potential, the choice of blowing agent far outweighs the importance of using bio-polyol in place of its fossil-derived counterpart.

Lastly, in Stage 3 of this environmental LCA, several SPF market penetration scenarios are considered from 2014 to 2022. For a medium annual increase (5%/year) in SPF (all SPF product types) market penetration specific to new building starts within the residential sector of Alberta, GHG reductions due to reduced operational building energy demand can lead to an average reduction of 360 Kilo-tonnes (kt) CO_2eq per year by the year 2022. If bio-SPF can gain a portion of this market penetration, then additional GHG reductions can be achieved. For instance, if a zero GWP blowing agent is utilized in this bio-SPF product, an additional GHG reduction could amount to 230 kt CO_2eq per year by 2022 when a 1% annual increase in bio-SPF residential insulation market share in Alberta is assumed. Considering the current price on carbon in Alberta is \$15/tCO_2eq, a significant amount of revenue could be generated provided this bio-SPF product is successfully commercialized and widely adopted in the province.

1. Introduction

As the constant push for more sustainable buildings continues, building codes are becoming stricter in order to reduce material and energy demand and to reduce greenhouse gas (GHG) emissions more effectively. Efficient performing technologies are vital to realizing these market demands. While minimum thermal resistance (R-value) requirements for exterior envelope insulation have become quite high in the colder regions of Canada, spray polyurethane foam is making more sense as an alternative to the conventional fibre glass batt (FGB) insulation. This is because a higher actual R-value per unit thickness and lower natural air infiltration rate through the building envelope can be achieved. In this project, a bio-polyol based spray polyurethane foam (SPF) and a more conventional FGB building insulation will be compared from an environmental life cycle perspective.

A recent study on insulation products has forecasted global demand for various insulation materials will rise 5.5% by 2016, and in Canada, demand for insulation materials is forecasted to grow by about 3% annually to over 400 million m^2 of R-1 value[1] in 2016 (Fredonia Group, 2013). The global market for polyurethanes has been growing at an average rate of over 7% per annum for the last 15 years, while Canada has witnessed substantial growth of 9.5% from 2011 to 2012 with an annual production of 55 thousand tonnes in 2012 (Verlag 2013). The utilization of SPF insulation and its continued growth in cold climates like Alberta's is promising since it has been found to be amongst the leading building envelope insulation materials in terms of providing a high thermal resistance (R) value in combination with a low air infiltration rate during building use.

An additional step forward in making SPF more sustainable is to utilize bio-based derivatives in the manufacturing of the material components that make up the foam. SPF can be divided into roughly a one-to-one ratio between its side-A isocyanate mix (TDI and MDI) and its side-B polyol (plus additives[2]) mix. Several recent publications (e.g. Zhang et al. 2014; Stirna et al. 2013; Kong et al. 2010; Narine et al. 2007;) and companies (e.g. Dow 2014; BASF SE 2014; Cargill Inc. 2014; Johnson Controls Inc. 2014; Mitsui Chemicals 2014; Rampf Ecosystems 2014; Emery OleoChemicals 2014) have developed/ commercialized various pathways for producing polyols from bio-oils such as castor, canola and soy oils,

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[1] R-1 value refers to a thermal resistance of 1 h-ft^2-°F/Btu which is in imperial units. To convert between imperial units and the international system of units (SI) the following factor is used: R_{SI} = 1 m^2-K/W = 5.68 h-ft^2-°F/Btu, where K= Kelvin, W=Watt, h=hour, ft^2 =square foot, °F = degree Fahrenheit, and Btu = British Thermal Unit.
[2] Side-B of SPF consists of mostly polyol but also contains other key ingredients such as a catalyst, blowing agent, fire retardant and surfactant.

while some recent researchers have even found ways of using a combination of crude glycerol and lignocellulosic residues (Li and Reeder 2011;) to produce this vital chemical of the polymer industry. These advancements are promising as most – if not all – of the environmental profiles of these bio-polyol products prove to be environmentally superior to its fossil fuel derived conventional counterparts while also maintaining favourable and even better physical properties for use in the vast array of applications that polyurethanes can be used for (Zhao et al. 2014; PlasticsEurope 2012; Omni-Tech 2010; Brennan et al. 2010).

In this analysis, an environmental life cycle assessment is undertaken for a bio-polyol based SPF product that is assumed to be used as a building envelope insulation material. These results will be benchmarked to both a more conventional SPF insulation as well as a more conventional insulation option, FGB. In addition to this bio-SPF product life cycle assessment (LCA) (Stage 1), the relative building operational energy and GHG reductions when SPF insulation is used in place of FGB insulation will be estimated (Stage 2) where several Albertan SPF market penetration scenarios will be considered in order to estimate total GHG mitigation potential due to the utilization of SPF insulation in the residential building sector of the province (Stage 3).

This analysis, as outlined in the following report, begins with a methodological description of the LCA which covers the goal, scope and major assumptions surrounding the life cycle inventory used in the life cycle impact assessment, where a detailed bio-SPF product description is provided. In addition, the methods surrounding the quantification of the building performance in terms of operational energy demand is provided and this is followed up with key assumptions used to estimate market penetration potential in Alberta. The results are then presented at the unit SPF product level alongside a benchmark comparison with other insulation products that fulfill a widely accepted equivalent building insulation function. Building performance results follow thereafter, and finally GHG mitigation potential at several market penetration levels are considered. A discussion of the analysis along with concluding remarks is then provided.

2. Methodology

2.1 Stage 1: Unit process based LCA of the bio-SPF product

A cradle-to-grave life cycle assessment (LCA) is undertaken for a canola oil derived polyol based SPF insulation material. The embodied environmental impacts due to insulation production and delivery, along with insulation application, use and maintenance, and end-of-life treatment are taken into account. The functional unit of the SPF product is the insulation of one square meter (m^2) of envelope area at a thermal resistance of R_{SI} = 1 m^2-°C/W for a 60-year time period. This functional unit is consistent with what is prescribed in the product category rule for building envelope thermal insulation (UL 2011). One SPF insulation product will be considered: a medium-density, closed-cell (CC) 2lb SPF product denoted as bio-SPF_{MD_CC} herein.

Main Stage 1 objectives:

- To provide a detailed results analysis and interpretation that illustrates the total and most important life cycle environmental impacts along the value chain of the bio-SPF_{MD_CC} product; and,
- To benchmark the climate change potential of this bio-SPF LCA with other LCAs of insulation products recently undertaken in literature.

2.1.1 Stage 1 Goal and Scope

A complete cradle-to-grave, attributional LCA is undertaken which follows the ISO 14040/14044 standards (ISO 2006a,b) as a guideline. Although several environmental impact categories will be considered, the main focus will be on life cycle greenhouse gas emissions or climate change impacts. In terms of life cycle inventory, the objective is to utilize the most market-relevant and recent data available, while also maximizing system completeness. To do so, the Ecoinvent version 2.2 database (Ecoinvent, 2014) is utilized as the background system. However, important background processes like electricity mixes in various regions of the life cycle, transportation distances and farming practices will be adapted to more accurately represent the market region in question.

It is quite common practice to use non-local databases as a background system in LCA studies when the region in focus does not have adequate life cycle inventory (LCI) (Ossés de Eicker et al. 2010). Although, the U.S. is catching up with their U.S. LCI database (NREL 2014), Canada is still quite behind, and therefore, the European-centered Ecoinvent v2.2 data base is used in this study because it is arguably the most complete (far more processes and emissions covered) and transparent (mostly gate-to-gate inventories) LCA database while still having a number of processes that span the globe (including in the U.S.). In doing so the quality of the background system gains in system completeness while it loses in regional technology relevance. To ensure the processes are as regionally relevant as possible several modifications are made in terms of key processes in the product value chain. Regional electricity mixes are adapted to key processes, canola yields/fertilizer/herbicide inputs and transportation distances for delivering intermediate materials along the SPF value chain are estimated based on regionally relevant information.

Characterization factors for several environmental midpoint impact categories from the ReciPe 2008 method (Goedkoop et al. 2012) are used. The majority of results focus on the climate change impact category which is a globally accepted and consistently applied methodology (Forster et al. 2007) while more aggregated results are presented for several other categories which can be found in appendix B. The names of all impact categories considered are the following and should be read as potential impact: climate change; terrestrial acidification; freshwater eutrophication; particulate matter formation; photochemical oxidant formation; human toxicity; terrestrial eco-toxicity; freshwater ecotoxicity; ozone depletion; marine eutrophication; marine ecotoxicity; ionizing radiation; water depletion; metal depletion; fossil fuel depletion; and urban land occupation.

The environmental benefits in the context of GHG reductions due to a decrease in operational building energy as a result of using SPF insulation instead of the more conventional fiberglass batt insulation are determined in the second and third stage of this project.

2.1.2 Stage 1: A System description of the Bio-SPF Insulation Product

In this section, a life cycle system description is given for the bio-SPF_{MD_CC} insulation product. Figure 1 provides a process flow diagram of the main foreground processes across the value chain of the bio-SPF_{MD_CC} insulation product considered.

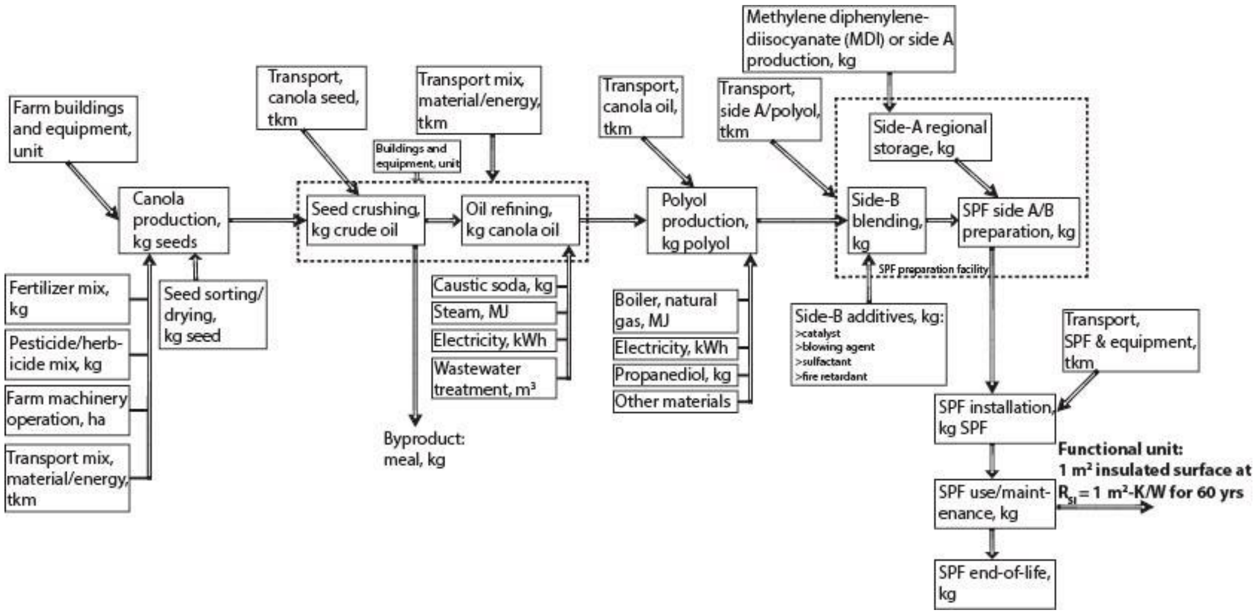


Figure 1: Process flow diagram of the SPF insulation life cycle system

The bio-SPF product under analysis is currently in its experimental phase conducted at the University of Alberta's Lipid Chemistry Group headed by Dr. Jonathan Curtis. In this LCA case study these SPFs are assumed to be distributed regionally across the Alberta market where the bio-polyol is assumed to be produced locally in Edmonton, AB. The bio-SPF insulation product is also assumed to be prepared locally in Edmonton. The following sub-headings describe the main processes throughout the value-chain of the bio-SPF product value chain.

Canola Production

The canola oil feedstock is assumed to be sourced from the Canadian province of Alberta where about 34% of Canadian canola production (14.4 Mega-tonnes/year (Statistics Canada 2014a)) currently occurs (see Figure 2 below).

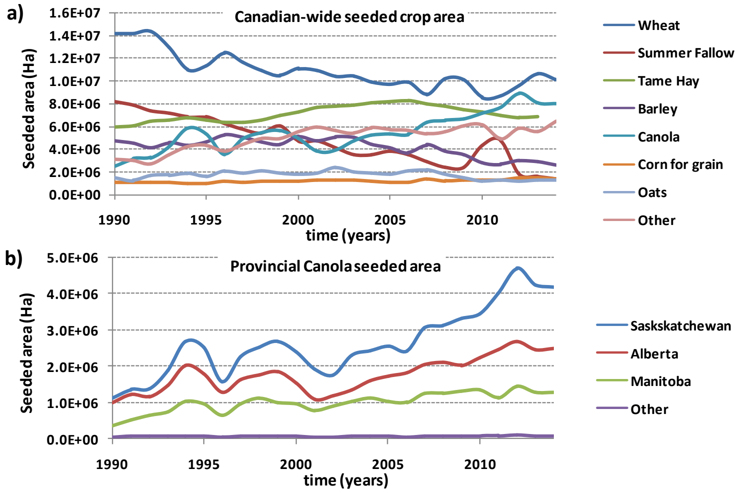


Figure 2: Canadian seeded crop area across time (1990 - 2013)

(Statistics Canada 2014a)

Since 2001, the canola produced in Canada has steadily grown leading to the second largest planted crop area across Canada. This makes canola oil a suitable feedstock for local Albertan polyol production. Additionally, the majority of canola crops today are well suited for no-tillage farm practices where only about 25% of recent seeded canola area remains to be farmed with conventional tillage (S&T 2010) and this tendency of no-tillage practices looks to be increasing (Smyth et al. 2011). Therefore, in this study no-tillage farming is assumed. A past ten year average Albertan canola yield is calculated to be 1960 kg canola/ha/year (Statistics Canada 2014a) and this is the yield assumed in this analysis.

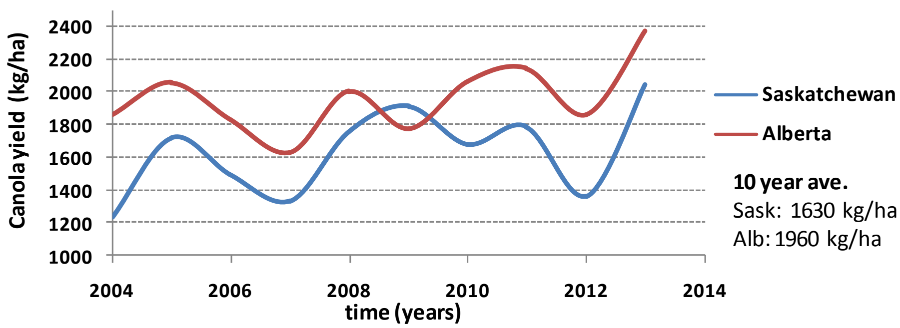


Figure 3: Average Canola yield in Alberta and Saskatchewan over time (2004-2013)

(Statistics Canada 2014a)

A ten year average (1999-2008) canola oil-in-seed content of 43.4% is assumed (Canadian Grain Commission 2009). In 2007 95.2% of canola crops were herbicide tolerant transgenic varieties.

Therefore, average seed and fertilizer inputs for transgenic canola plots based on a 650 canola farm survey (Canola Council 2001) is used to derive the fertilizer inputs assumed in the LCI:

Table 1: Average fertilizer requirements for transgenic canola production and N source

Fertilizer	kg/t canola
N	48.7
P2O5	17.1
K2O	4
Seeds	8.4
Nitrogen Source	N fraction
Ammonia	0.2788482
Urea	0.5434125
Ammonium Sulphate	0.0719874
Urea Ammonia Nitrate	0.1057519

(source: Canola Council 2001)

Similarly detailed data on herbicide application is based on values reported in Smyth et al. (2011) and further chemical input (fungicide/pesticide) along with farm machinery use is supplemented with LCI data from a detailed German study (Jungbluth et al., 2007). An average N_2O emission factor for the region is used: 0.0075 kg N_2O per kg N in the fertilizer applied and N content in the canola residues left on the field (Rochette et al. 2008). Canola residues/roots make up about 85% of the total canola plant upon harvest and 8 grams N/kg residue is assumed (Janzen et al. 2003). Given the high adoption rate of no-to-low-tillage canola farming practices, it has been observed that such plots act as a net carbon sink. West and Post (2002) determined that changing tillage practices from conventional tillage to zero-tillage can sequester carbon at a rate of 57 g ± 14 grams-$m^{-2}year^{-1}$ and this value is used in this analysis (see Appendix A for gate-to-gate LCI tables).

Canola Crushing and oil refining (process description based on Mag 2014)

Once dried the canola seed at farm gate is transported to a seed crushing and oil refining facility where the seeds are first cleaned and graded. The seeds are then preheated to about 30-40°C before being steam-cooked at about 75-100°C allowing for the seed cells to rupture for easy release of the oil. The seeds are first crushed in a screw-press reducing oil content in the seeds from 43.4% to around 16-20%. The remaining press-cake is then conveyed to the solvent extractor where the oil content in the meal byproduct is leached down to about 1%. The cold-pressed and solvent extracted oil are then combined and degummed using a mixture of phosphoric acid and water which removes phosphatides in the oil. Residuals from the degumming process (including some oil) are added to the meal which increases the oil content in the meal to around 2-3%.

A portion of the above oil content of 43.4% seed mass will be lost to the meal by-product. Here we assume that 39.6% of the oil in the seeds is finally output as refined canola oil (Jungbluth et al. 2007). The remaining portion of the canola seed is assumed to be livestock meal. Since a by-product exists, allocation is required and economic allocation is deemed most suitable for the given products because there is a large price difference between the two commodities canola oil and canola meal. A recent (2010-2013) Canadian four year average price for degummed canola oil ($1140/tonne) and canola meal ($290/tonne) is used to undertake the economic allocation procedure (Canola Council 2014). An allocation factor of 72.1% is derived for the canola oil product. Auxiliary inputs for the seed crushing/oil refining process include those for transport, electricity, natural gas based heating, the hexane solvent, phosphoric acid (for degumming), bentonite clay (for bleaching) and the treatment of sewage at the facility (see Appendix A for gate-to-gate inventory).

Bio-polyol production

Due to highly sensitive and proprietary data surrounding this process it cannot be explained in detail here. Canola oil is the primary input to the bio-polyol batch process which consists of three distinctive steps in its synthesis: expoxidation of the canola oil, formation of the polyol and fractionation to separate the polyol to purity. Energy inputs are estimated from a recent study (Omni-Tech 2010) and material inputs are based recent communication with Dr. Curtis.

SPF preparation, installation and characteristics

With a high density, and R-value per unit thickness, bio-SPF_{MD_CC} is particularly useful in floor and attic cavities because these planes of the building envelope require a higher R-value than the walls (see section 2.2.2). Several technical specifications assumed for the bio-SPF_{MD_CC} are provided in Table 2 below.

Table 2: Key SPF product specifications

	SPF_{MD_CC}
R_{SI} @ 50 mm (m2 °C/W)	1.83
R-value @ 50 mm	10.4
Core density (kg/m3)	39
Mixing ratio (A side:B side)	50 / 50
Hose heater temperature (°C)	49 - 60
Substrate temperature (°C)	-9.4 - 38

Source: (see Pinnacle West Inc. 2014)

The thermal resistance of the SPF insulation is assumed to increase linearly with thickness. Table 2 shows that at a thickness of 50 mm the bio-SPF_{MD_CC} product has an R_{SI} value of 1.83 m^2°C/W (multiply by 5.68 to go from R_{SI} to imperial R-value units).

Rigid SPF products (like those used for building insulation) consist mainly of two chemicals: the methylene-diphenelene diisocyanate (MDI or A-side) and the polyol blend (B-side). The B-side also consists of several additives which include the blowing agent, flame retardant, catalyst and surfactant. SPF is made when this insulation is applied by combining MDI (A-side) with an equal volume of a polyol blend[3] (B-side). The A and B side react and expand at the point of application in the building envelope to form polyurethane foam. The formed-in-place SPF provides thermal insulation, air sealing properties and structural benefits in the case of bio-SPF_{MD_CC}. The A-side is essentially the same for all SPF insulation products while the B-side composition can change depending on the desired properties of the SPF. In this analysis the B-side mix is based on a combination of product description by Kong (2014) and average compositions presented in SPFA (2013). In North America, the A-side is manufactured by four U.S. based chemical manufacturing companies with processing facilities located in Texas and Louisiana (SPFA 2013). In this study the bio-polyol blend is assumed to be prepared in an industrial park located in North East (NE) Edmonton. Most of the primary chemicals used in the B-side formulation are processed in Texas, Louisiana and Virginia. In this study both SPF sides are prepared for application where the bio-polyol is produced. The prepared SPF sets are then stored in a local warehouse where it is then distributed throughout the province and beyond for building insulation projects.

In Table 3, a breakdown of the ready-to-mix bio-SPF_{MD_CC} product composition is provided.

Table 3: A-Side and B-Side SPF Composition (as a mass % of complete SPF mix)

		SPF_{MD_CC}		Covered in this LCA
A-Side (MDI)				
MDI (Methylene diphenyl diisocyanate)		50		yes
B-Side (Polyol + additives)				
Bio-Polyol		37.5		yes
Flame retardent	TCPP[1.]	2		yes[2.]
	Brominated	3		no
Blowing agent	Reactive (H2O)	1		yes
	Physical (Methyl Formate)	4.25		yes
Catalysts	Amine	1.5		yes
	Metal	0.25		no
Surfactants	Silicone	0.5		yes
	total	100	%	

Source of general composition: SPFA (2013) and Kong (2014)
1. TCPP = Tris (1-chloro-2-propyl) phosphate
2. Based on mass balance of main chemical inputs assuming 95% yield
3. Only off-gassing (H2O reacts with MDI to form CO2) during installation is considered

[3] The polyol blend consists of a mix of polyols, fire retardant, blowing agent, catalyst and other additives.

The A-side of SPF consists solely of the MDI material which is assumed to be 50% of the SPF product since the A- and B-side are sprayed together in a one-to-one ratio (SPFA 2012). The mixture of the polyol B-side governs the desired characteristic of the resulting foam and it consists of several chemicals as can be seen in Table 3. During experimentation several blowing agents are currently being considered in the optimization of the bio-SPF_{MD_CC} product (Curtis 2014). One objective of this bio-SPF project is to select a climate friendly blowing agent and methyl formate has been selected as one of the best choices while HFC-245fa and water are also being considered (Curtis 2014). Therefore, the main results in Stage 1 assume that the blowing agent is a combination of water and methyl formate while results for HFC-245fa/water and other blowing agents are also presented.

In Table 4 the mass of each SPF product consumed per *f.u.* is depicted along with foam thickness, and assumed yield and scrap losses.

Table 4: Mass SPF consumed per functional unit (f.u.)

	SPF_{MD_CC}
mass SPF in place per f.u. (kg)	1.07
mass SPF consumed per f.u. (kg)[1]	1.17
thickness per f.u. (mm)	27
yield losses (mass fraction)[4]	0.03
scrap losses (mass fraction)[4]	0.04

1. Includes losses (yield, scrap and blowing agent)
2. Source: Own assumption
3.90% of PE covers FGB, 10% covers frame material
4. Source: SPFA (2012)

The water in the B-side mix which is used as a blowing agent reacts with some of the MDI to form CO_2 immediately when both sides come into contact during SPF application. All of the water in the bio-SPF_{MD_CC} product is assumed to react with MDI to form CO_2 (mass CO_2 = mass H_2O*44/18 where 44 and 18 are the molar weights of CO_2 and H_2O, respectively) (SPFA 2012). This water/MDI reaction results in a product yield loss as can be seen in Table 4 above. Additionally there are losses due to the SPF product that adheres to the building frame surface and other unwanted areas where it will need to be scraped off; these scraps are assumed to be treated as waste in a landfill.

The A- and B-side of SPF are usually contained in 55 gallon drums when transported and utilized at the construction site. The hardware required to apply the SPF insulation includes the following: the proportioner, the guns, the feed system, a compressed air supply, a power supply and safety gear. In this LCA, the energy requirement for the power source is included, while compressed air and other capital requirements for SPF application equipment are beyond the scope of this analysis. A diesel generator is assumed for the on-site power supply and it is used to mix, heat and pressurize the mixture while also ensuring that the A- and B-side are properly proportioned when exiting the SPF gun.

Transportation distances assumed between the main processes

In Canada the majority of canola is produced throughout the provinces of Alberta, Saskatchewan and Manitoba as Figure 4 illustrates.

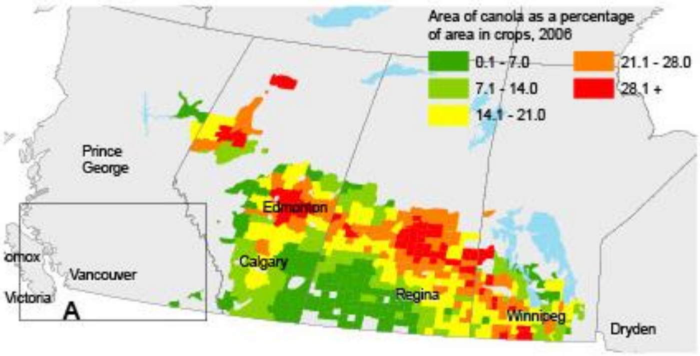


Figure 4: A broad overview of where canola is grown throughout Canada (adapted from Casséus 2006)

In this analysis only Albertan produced canola oil is assumed for bio-polyol production and the canola seed is assumed to be transported by truck from farm to canola processing plant. As it is shown in table 5 there are currently fourteen canola processing plants in Canada where four are located in the province of Alberta and one is located just North of Edmonton in Fort Saskatchewan (Canola Council 2014).

Table 5: Canola crushing/refining/packaging plants in Canada and their annual production capacities

Company	location	Capacity (t/yr)
Bunge	Fort Saskatchewan, AB	270000
JRI	Lethbridge, AB	440000
ADM	Lloydminster, AB	1020000
Cargill	Camrose, AB	0*
Dreyfus, JRI	Yorkton, SK	850000
Bunge	Nipawin, SK	475000
Cargill	Clavet, SK	1500000
Bunge	Harrowby, MB	510000
Bunge	Altona, MB	875000
Viterra	Ste. Agathe, MB	350000
Bunge	Hamilton, ON	275000
ADM	Windsor, ON	400000
TRT-ETGO	Becancour, QC	1020000

*Start-up will begin upon the 2014 canola harvest

(Canola Council 2014)

In this study, all of the canola oil that is used to produce the polyol is assumed to be sourced from the canola processing plant located in Fort Saskatchewan and the polyol production plant is assumed to be located in the East Edmonton industrial park where side-A blending and SPF preparation are also assumed to take place at the polyol production facility. Table 6 shows the assumed distances between the main SPF manufacturing facilities, regional storage, and application site.

Table 6: Assumed road distances between key processes in the SPF value chain

Material transported	Origin	Destination	transport mode	distance (km)
Canola seed	Canola production (various Albertan canola farms)	Bunge canola processing plant, Fort Saskatchewan	truck (50%); rail (50%)	250
Canola oil	Bunge canola processing plant, Fort Saskatchewan	Polyol production/bleding and SPF preparation plant, NE Edmonton	truck (100%)	20
Side-B	Side-B production, Near Houston, Texas	Polyol production/bleding and SPF preparation plant, NE Edmonton	truck (100%)	3693
SPF sets	Polyol production/bleding and SPF preparation plant, NE Edmonton	SPF regional storage, Edmonton	truck (100%)	10
SPF sets	SPF regional storage, Edmonton	Construction site (not specific)	truck (100%)	100

MDI is produced at only two places in North America: Houston and Louisiana. In this analysis MDI is assumed to be produced near Houston. Finally, for the distance from regional storage (at Spraysulate Inc. facilities) to the construction site, a general assumption of 100 km is chosen.

2.2 Stage 2: Building performance--operational energy demand and associated GHG emissions

In the second stage of this analysis SPF and its operational performance are compared with the most conventional insulation (fibre-glass batt (FGB)) on the Albertan market ensuring that it complies with the 2011 National Energy Code for Buildings (NECB) as a baseline (Government of Canada, 2014). This code contains a set of 'prescriptive' energy-efficiency measures that should be included in new buildings. By comparing the heating energy requirements between the building with the NECB-compliant SPF insulation and the NECB-compliant baseline case with the more conventional (FGB) insulation, the annual energy savings are estimated along with the associated reductions in GHG emissions. Life cycle GHG payback periods are also tabularized.

Main Stage 2 objectives:

- To estimate the difference in annual energy demand required for building operation when the given building uses either SPF or FGB (NECB (2011) compliant) insulation;

- To calculate the associated life cycle GHG emissions due to annual building energy demand for each insulation utilization case; and,
- To calculate the life cycle GHG payback periods when the SPF building cases are implemented in place of the NECB compliant FGB baseline case.

Since the building is assumed to be identical in both insulation application cases, Stage 2 consists of undertaking a process based attributional screening LCA. The reason why it is a screening LCA is because only the main differences between the two insulation cases (SPF vs. FGB) are being analyzed. This means that all other life cycle material and energy requirements for the house are not considered. However, knowledge surrounding the design and specifications of the building will be required in order to accurately model the space heating and total energy demand of building operation.

Although several environmental impact categories could be considered, the sole focus in terms of environmental impacts will be on life cycle GHG emissions or climate change impats. In terms of life cycle inventory, the objective is to utilize the most market relevant and recent data available, while also maximizing system completeness.

The functional unit for this comparative LCA analysis in Stage 2 will be the following: one square meter of building floor space heated for one year. Whole building annual heating requirements are also quantified and compared between the several insulation cases. The life cycle impact due to the insulation material as calculated in Stage 1 is also included in order to calculate any GHG payback periods due to the SPF product having a higher production impact than the FGB insulation (see Stage 1 analysis for these product based results) while achieving superior performance during building operation.

Stage 2 System Description

In this section, a brief description is given for each of the building types analyzed—a mid-rise apartment building and a detached house.

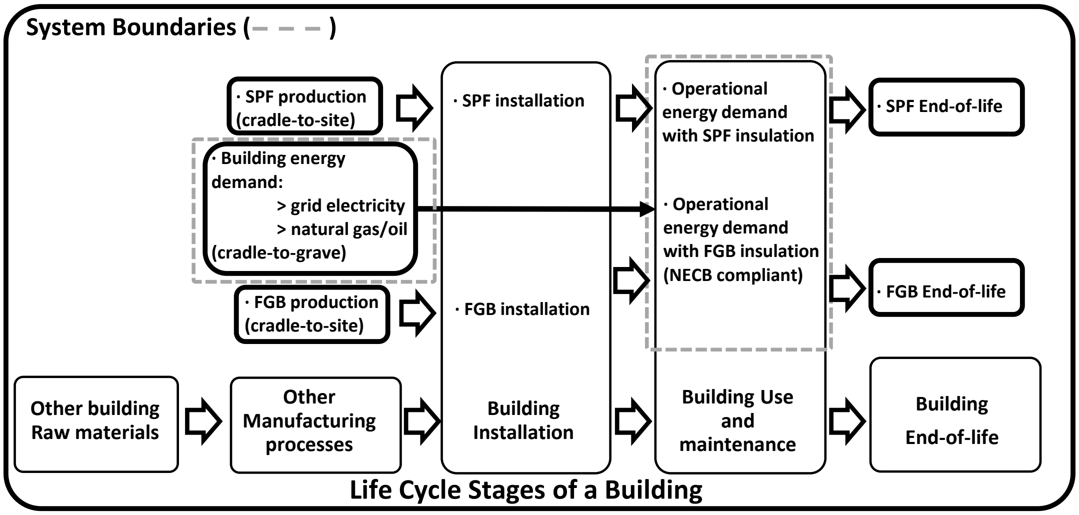


Figure 5: Process flow diagram of life cycle system boundaries covered in Stage 2

The box outlined with grey-dotted lines in Figure 5 illustrates the life cycle system boundaries considered in Stage 2 of this project. Essentially, the life cycle impacts of the energy requirements (cradle-to-grave) for building operation are considered. However, when calculating the GHG payback periods the LCA results from Stage 1 will be utilized.

Apartment Building Characteristics

The apartment building is assumed to have five above grade floors along with a below grade parking garage. The building is rectangular with a flat roof and a perimeter of 37.5x19.8 m making the building area 743 m^2 while the gross floor space is 3712 m^2. The floor-to-floor height is 2.7 m is 2.4 m. The construction is assumed to be wood frame (2x6s) with 115.24 cm spacing on center. The air infiltration of the core and perimeter are assumed to be the same and they differ across the building simulation cases (see below). The air infiltration rates—measured in air changes per hour (ach)—range from 0.5-0.75 ach for the NECB compliant FGB insulated building simulations and 0.12-0.18 ach for the SPF insulated configurations. Fifteen percent of the exterior wall area of each side of the apartment is assumed to be windows. A single season schedule is assumed where dwellers return to their apartment at 5pm on all days and leave at 7:00 am on Monday-Friday and 11:00 am on holidays and weekends. The in-envelop building area is allocated to the following room types: 71% dwelling units, 16% corridor, 7% utility/warehouse, and 6% laundry/washing. The thermostat set-point for occupied heating is assumed to be 20 °C while no space cooling is assumed to be required for any of the specified locations in Alberta. The space heating system for the apartment is assumed to be a centralized convection/forced air natural gas furnace system and this furnace system has a thermal efficiency of 80.6%.

Detached House Building Characteristics

The modelled detached house is assumed to have two above grade floors with a crawl space open to ambient conditions. The building footprint is square with a 25° pitched roof with a perimeter of 9.39x9.39 m making the building area 88.2 m^2 while the gross floor space within the envelope is 176 m^2. The floor-to-floor height, framing, relative window-to-wall %, use schedule, thermostat set-point, heating system and air infiltration rates are assumed the same as in the apartment building simulation. The in-envelop building area is allocated to the following room types: 85% dwelling space, 8% garage, and 7% laundry/washing.

Comparing insulation effectiveness between FGB and SPF

Interestingly, the rated R_{SI} value per unit thickness for FGB is typically about half the R_{SI} values of the bio-bio-SPF_{MD_CC} product. However, the actual R_{SI} can be significantly lower than the rated R_{SI} value. The main reasons for this decrease in R_{SI} are due to heat bridges created from structural materials passing through the thermal insulation, and inadequate application of the insulation leaving gaps in envelope cavities. The rated R_{SI} value also ignores real world climatic conditions such as outside wind, water vapor and temperature because it is valuated based on laboratory testing (i.e. constant temperature, no air flow, 0% moisture).

In order to conduct a fair comparison between the two insulation materials the actual R_{SI} of each insulation product and the air infiltration through the insulated envelope needs to be compared between the products and quantified. This requires knowledge of resistance to air penetration, to free water and to vapor drive. In general it has been found that SPF insulation out-performs FGB insulation in terms of actual R_{SI} value and air infiltration, because of its air impermeable properties and its ability to routinely cover the entirety of a cavity with negligible gaps. In fact, spray-in-place SPF is the only material, when properly applied, completely fills in the corners, cripples, double studs, and bottom/top plates etc. The rated or actual R_{SI} value of a material is of little interest or consequence if air can get past it. To account for these differences only the range of air infiltration rates for the whole building is assumed to differ significantly (see Table 8).

2.2.1 Stage 2 Key Assumptions and Limitations

The CAN-QUEST Beta software (SCC 2013) is used to undertake the building energy simulation. This software has recently been released (2013) for Canadian climate conditions and NECB (2011) compliance baselines. CAN-QUEST uses the DOE-2-derived (visit http://www.doe2.com/) simulation engine which is one of the most widely recognized building energy analysis programs in use today. CAN-

QUEST´s engine extends and expands DOE-2´s capabilities in several important ways, including interactive operation, dynamic/intelligent defaults and improvements to numerous longstanding shortcomings in DOE-2. CAN-QUEST Beta calculates hour-by-hour building energy consumption over the entire year (8760 hours). A baseline building model that assumes a minimum level of efficiency (i.e. minimally compliant with NECB (2011)) is created and used to estimate annual energy savings due to the energy efficiency measures (EEM) put in place. In this project the EEM considered is switching from NECB minimum compliant R_{SI} values (assuming mostly FGB insulation is used) to an equal or higher insulation R_{SI} value with the use of SPF insulation. The insulation requirements for each of the building energy simulation runs are shown in table 7.

Table 7: Assumed insulation R-values and assumed building locations for each of the building model runs—fiber glass batt insulation base cases and SPF insulation configurations

		NECB compliant insulation - base case		
Location	Climate zone	Roof	Walls	Floor
Calgary	Alberta A	R-32 batt	R-22.3 batt	R-32 batt
Edmonton	Alberta B	R-38 batt	R-27 batt	R-38 batt
Fort McMurray	Alberta C	R-38 batt	R-27 batt	R-38 batt

		SPF insulation - config. 1			SPF insulation - config. 2			SPF insulation - config. 3		
Location	Climate zone	Roof	Walls	Floor	Roof	Walls	Floor	Roof	Walls	Floor
Calgary	Alberta A	R-32 SPF	R-22.3 SPF	R-32 SPF	R-36 SPF	R-22.3 SPF	R-36 SPF	R-40.5 SPF	R-30 SPF	R-40.5 SPF
Edmonton	Alberta B	R-38 SPF	R-27 SPF	R-38 SPF	R-45 SPF	R-27 SPF	R-45 SPF	R-50 SPF	R-35 SPF	R-50 SPF
Fort McMurray	Alberta C	R-38 SPF	R-27 SPF	R-38 SPF	R-45 SPF	R-27 SPF	R-45 SPF	R-50 SPF	R-35 SPF	R-50 SPF

*to convert from stated R-value to R_{SI} value divide by 5.68.

Table 7 shows the minimum requirements for NECB compliant buildings. Canada is divided into several climate zones for which colder zones with greater degree-heating days require stricter R-values. The NECB (2011) states that Alberta climate zone B and C have the same minimum R-value requirements while climate zone, Alberta A, is significantly less. Three SPF configurations are assumed. SPF configuration 1 uses the same R-values as the NECB minimum requirements. SPF configuration 2 assumes that the wall R-value remains the same as the NECB minimum requirements while the roof and floor are both increased by the same amount (+4 R-value for Calgary and +7 R-value for Edmonton and Fort McMurray). Lastly, SPF configuration 3 assumes the R-values of the entire envelope are significantly higher than the NECB base case. The R-values for the regions of Edmonton and Fort-McMurray are kept the same as each other in order to be consistent with the stated NECB minimum requirements for those climate zones.

Table 8: Air changes per hour—values assumed for the NECB FGB base cases and the SPF configurations

NECB FGB building base case			
Air change per hour	0.5	0.625	0.75
SPF configurations			
Air change per hour	0.12	0.15	0.18

Another important parameter in buildings that can be significantly affected by insulation characteristics is the natural air infiltration rate of the building measured in units of air changes per hour (ach). Based on confirmation from a regional SPF supplier (SWD 2013) the ach ranges chosen when either FGB or SPF insulation are utilized are 0.5 to 0.75 and 0.12 to 0.18, respectively. These natural air infiltration ranges are split into three values—high, average and low (see Table 8). As will be seen in the Stage 2 results section, the rate of natural air infiltration is an important parameter when it comes to annual space heating demand.

All cases presented in Table 7 (3 base cases and 9 SPF cases) are then modelled with the appropriate ach values as shown in Table 8 creating thirty-six simulations per building type.

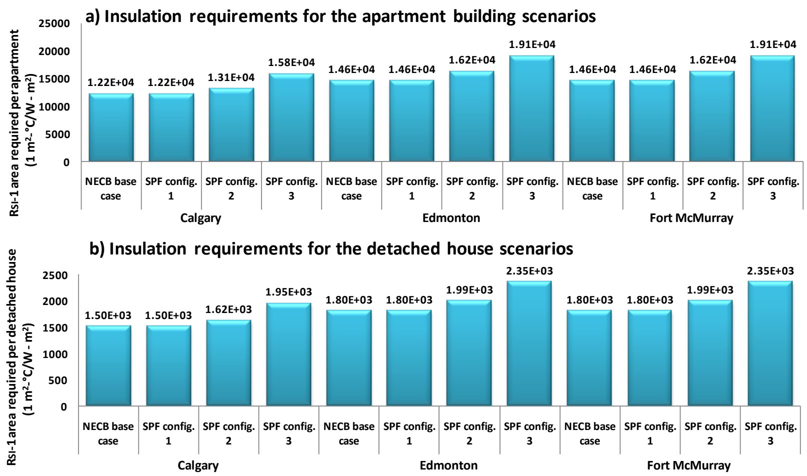


Figure 6: The quantity of R_{SI}-1-m²equivalent insulation required for each apartment (a) and detached house (b) scenario

Based on R-values from Table 7 and apartment envelop geometry, the R_{SI}-1 area required for each apartment/insulation case has been estimated and these values are illustrated in Figure 6 above.

Life cycle climate change impact from building energy requirements

Electricity requirements for the building cases are assumed to be supplied from the Alberta grid. Natural gas is the assumed fuel source used for the domestic hot water heating requirements in both space heating cases. As can be seen below in table 3 a recently reported snapshot of Alberta's electricity mix indicates that there is a high rate of life cycle GHG emissions per kWh consumed due to the coal and natural gas components of the mix.

Table 9: Alberta´s electricity mix (2012)

	GWh	Percentage
coal	38272	52%
natural gas	27238	37%
hydro	2319	3.2%
wind	2640	3.6%
biomass	2089	2.9%
others	359	0.49%
total	72917	100%

(source: Government of Alberta 2013)

The life cycle GHG emission factors used for Alberta electricity and natural gas are given in Table 10 below.

Table 10: Life cycle GHG emission factors used in stage 2 of this study (kg CO_2eq/kWh consumed at building)

	units: kg CO_2eq/kWh	source:
Alberta electricity	1.06	NRCan 2012
Natural gas (combusted at consumer)	0.238	ICF 2012

2.3 Stage 3: Bio SPF Market Penetration Potential in Alberta

In Stage 3 of the analysis several SPF market penetration scenarios within the region of Alberta are chosen in order to estimate the potential GHG and energy reductions due to the adoption of SPF building insulation. To do so performance results from Stage 2 are used in combination with residential building statistics. Only the residential sector is considered for this market penetration analysis. Figure 7, a) depicts a time-series of the growth in the residential sector of Alberta in terms of total floor space and number of household units (NRCan 2012b). Additionally the trend of average floor space per household unit is also shown.

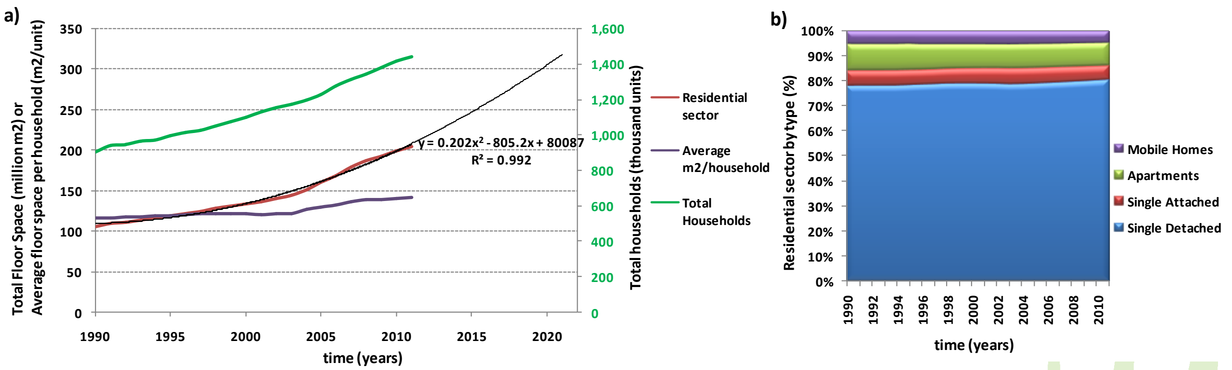


Figure 7: Alberta residential sector, a) total residential floor space (left axis), average floor space per household (left axis) and total number of households (right axis); b) residential sector by share of building type

A best fit curve is used to predict the growth in residential floor space in Alberta and this growth curve is used to estimate the market penetration of SPF insulation within the residential sector of Alberta. To differentiate between building types, Figure 7, b) indicates that the share between apartment dwellings and single homes has remained relatively constant (Statistics Canada 2014b). Here a ten-year average from the time-series in Figure 7, b) is used: 85.4% for single homes and 9.4% for apartments. The share of mobile homes is not included in this analysis. Table 11 provides the three market penetration scenarios considered for the SPF building insulation adoption rate within the residential sector of Alberta (excludes mobile homes).

Table 11: SPF building insulation market penetration scenarios

% of residential sector insulated with SPF			
year	Low	Medium	High
2014	5%	5%	5%
2015	7%	10%	15%
2016	9%	15%	25%
2017	11%	20%	35%
2018	13%	25%	45%
2019	15%	30%	55%
2020	17%	35%	65%
2021	19%	40%	75%
2022	21%	45%	85%

A low, medium and high market penetration scenario is used to estimate the building energy and GHG reduction potential associated with the adoption of SPF insulation. Building energy savings--both absolute and in relative terms--are particularly climate sensitive. As is shown in Figure 8, the share of new housing starts from the past four years for the regions of Calgary, Edmonton and Fort McMurray are used to divide the total residential housing growth in Alberta in order to provide at least a small degree of differentiation between climate zones in the province (Statistics Canada 2014d).

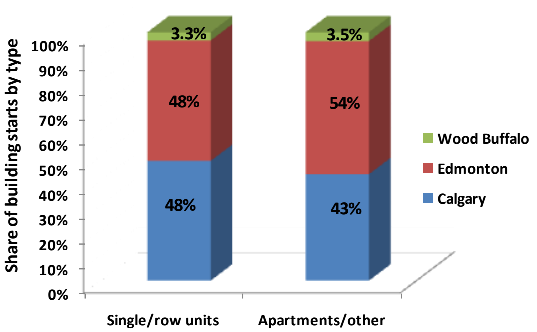


Figure 8: Four year (2010-2013) housing starts in the three key regions considered in stage 2 of this analysis, used as proxies to divide province-wide residential sector growth. (Statistics Canada 2014d)

The summation of these three census metropolitan areas is fairly representative covering about 52% of all province-wide housing starts in 2013 (Statistics Canada 2014d).

In order to estimate GHG emission reductions due to the bio-SPF_{MD_CC} product replacing a conventional SPF_{MD_CC} product currently dominating the Alberta market today--one that uses fossil-based polyol and the HFC-245fa blowing agent--Stage 1 results and an estimate of insulation required per m^2 gross floor space is used. The life cycle GHG emissions due to this conventional SPF_{MD_CC} product is explained near the end of the Stage 1 results section. Table 12 below takes the assumed insulation required to meet NECB minimum requirements (see configuration 1 in Figure 6) and it is divided by the gross floor space of each building type.

Table 12: RSI-1 Insulation required per m² gross floor space

	Apartment	Detached house
Calgary	3.28	8.52
Edmonton	3.92	10.20
Fort McMurray	3.92	10.20

Similar to the assumed SPF market penetration scenarios presented in Table 11 above, the following market penetration scenarios are assumed for the bio-SPF_{MD_CC} product where a low (0.5%/yr), medium (1%/yr) and high (1.5%/yr) residential market penetration is assumed.

Table 13: SPF building insulation market penetration scenarios

% of residential sector insulated with bio-SPF_{MD_CC}			
year	low	medium	high
2014	0%	0%	0%
2015	0.5%	1.0%	1.5%
2016	1.0%	2.0%	3.0%
2017	1.5%	3.0%	4.5%
2018	2.0%	4.0%	6.0%
2019	2.5%	5.0%	7.5%
2020	3.0%	6.0%	9.0%
2021	3.5%	7.0%	10.5%
2022	4.0%	8.0%	12.0%

Similar to Table 11, the bio-SPF_{MD_CC} penetration scenarios are relative to the overall growth in gross residential floor space in Alberta as according to Figure 7 above. For example, the medium penetration scenario assumes that by 2022, the bio-SPF_{MD_CC} insulation will have attained 8% of new residential building starts.

3. Results and Analysis

3.1 Stage 1 Results and Analysis

Figure 9 below illustrates the life cycle climate change impacts measured in kg CO_2eq per functional unit (*f.u.*) and how they are distributed across the main processes in the bio-SPF$_{MD_CC}$ product value chain. The impact that is attributed to each process in the legend includes both direct and indirect impacts due to the required demand of the given foreground process. For example, the process labeled ´*MDI, to SPF production*´ includes direct impacts from the MDI production facility as well as all upstream inputs required to produce the MDI product required for the given *f.u.* in this analysis.

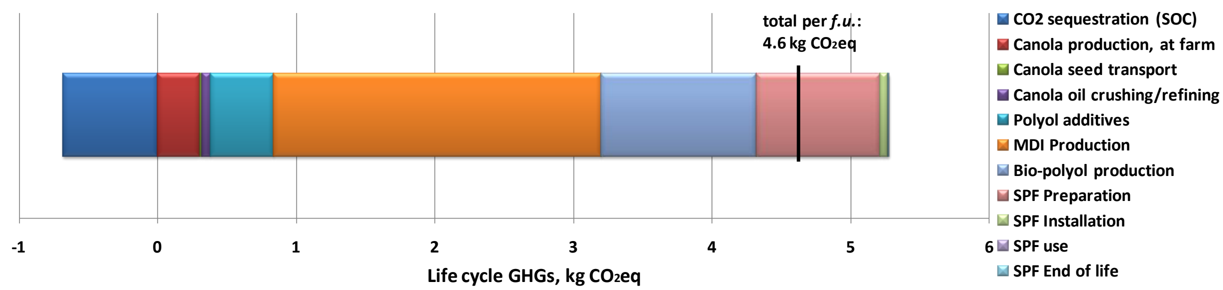
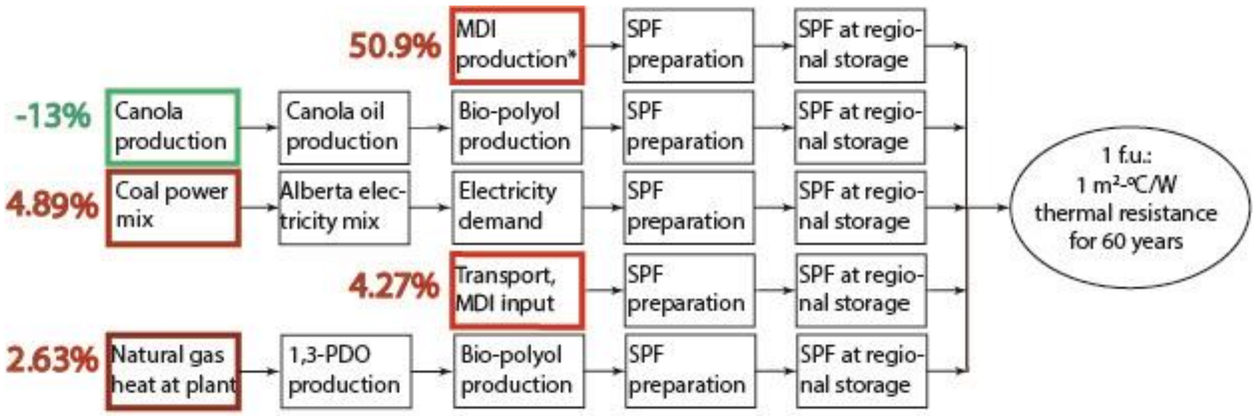


Figure 9: Cradle-to-Grave Climate Change Impact (kg CO_2eq) due to each foreground process (direct + indirect) per functional unit of the bio-SPF$_{MD_CC}$ product

The majority of the climate change impact is due to the MDI (side-A) value chain contributing around 51% or 2.36 kg CO_2eq/*f.u.*. The next top three positive contributing processes are bio-polyol production (24.5%), SPF preparation (19.3%), and the impact due to producing the additives that are blended with the polyol making up side-B (9.98%). Since net biogenic carbon sequestration is assumed to be negative (West and Post 2002) for the no-tillage canola farm process, a significant credit of -0.69 kg CO_2eq/*f.u.* is gained. Figure 10, below, illustrates the most important global warming hotspots where a structural path analysis in used to illustrate the top five contributing pathways of this product system. Each row of processes depicts the pathway to the most important hotspots where the process in the red (positive impact) or green (negative impact) box is where the given percentage of the total life cycle climate change impact per *f.u.* is actually occurring.



Includes impact from direct and indirect (cradle-to-gate) upstream inputs

Figure 10: The top 5 contributing pathways for climate change impact (% of total impact: 4.59 kg CO_2eq/f.u.). The red/green indicates at what process the given percentage of total impact per f.u. is occurring.

As mentioned earlier, slightly over half of the environmental impact is due to the production and distribution of side-A or diisocyanate. The no-tillage canola farming leads to net climate benefit as CO_2 continuously gets sequestered and stored as organic carbon in the soil contributing to -13% of the total climate change impact. The third most significant climate change hot spot, at 4.89%, is due to the coal fuelled electricity demanded by the SPF preparation plant. The fourth hot spot is due to transporting MDI (side A) from the MDI plant near Houston to the SPF preparation facility assumed to be located in NE Edmonton. The fifth climate change hot spot is due to the natural gas heat source required in producing the 1,3-PDO (1,3-propanediol) required for bio-polyol production.

Sensitivity Analysis

The sensitivity analysis presented next indicates key changes in the total life cycle climate change impact per functional unit when several parameters are altered: density of the insulation product, rated R_{SI} value effectiveness and choice of blowing agent.

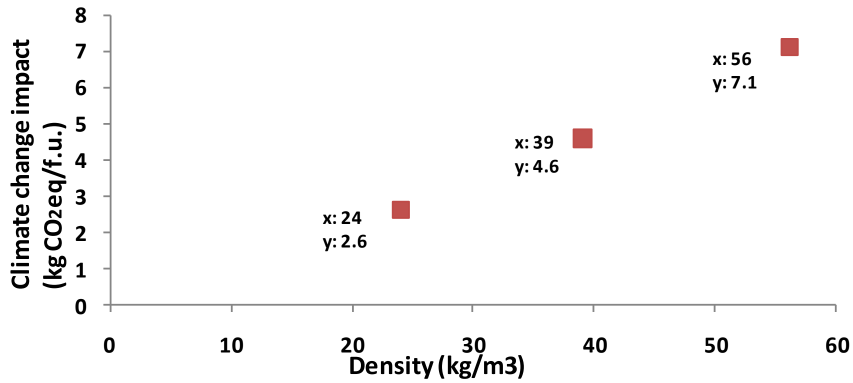


Figure 11: Cradle-to-grave climate change impacts (kg CO_2eq) per functional unit for each insulation product as a function of changing density (kg/m3).

SPFA (2013) reports that the density of SPF_{MD_CC} can vary from 24 to 56 kg/m^3. The results in Figure 11, above, depict the total climate change impact per functional unit for the lowest (24 kg/m^3) density, the assumed density (39 kg/m^3) and the highest density (56 kg/m^3) for the bio-SPF_{MD_CC} product. These results assume that the rated R_{SI} value remains constant and as assumed in the main results (see table 2). As the density increases, a greater mass of each insulation product is required to fulfill the functional unit. These calculations are limited since they assume that the SPF composition remains constant and therefore the quantity of blowing agent increases linearly with density. It may be the case that less blowing agent is needed as density increases. Due to a lack of specific information more detailed results cannot be attainted for this important sensitivity parameter.

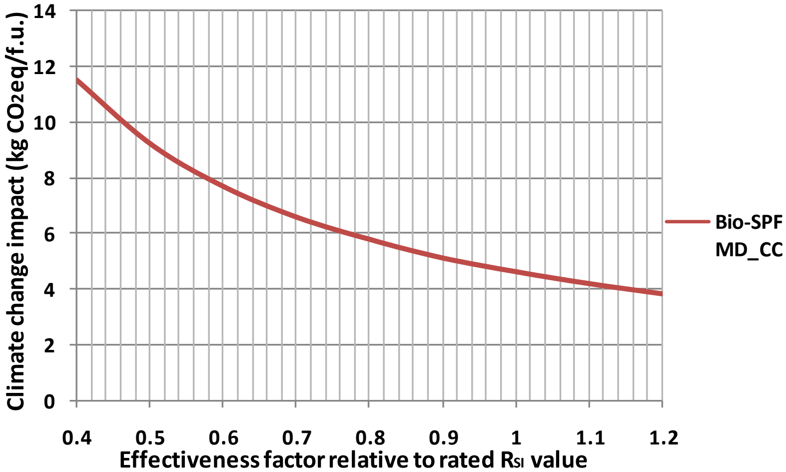


Figure 12: Cradle-to-grave climate change impacts (kg CO_2eq) per functional unit for each insulation product as a function of rated R_{SI} value effectiveness.

In Figure 12, the life cycle climate change impacts per *f.u.* vary as a function of effectiveness factor relative to the rated R_{SI} value. For example, if the actual R_{SI} value is 70% of the rated R_{SI} value, then the corresponding climate impact is due to the production of enough insulation material to fulfill the functional unit (i.e. 1/0.7 = 1.4 times more input) . These results are important because the measured R_{SI} value during the operation of the building can likely be lower than the rated value. Some recent studies have found that the actual R_{SI} value can be significantly less for the FGB product while remaining relatively close to the rated R_{SI} value for SPF products.

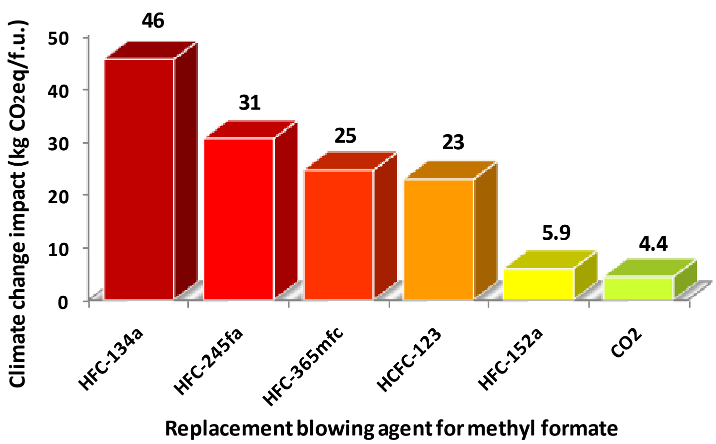


Figure 13: Cradle-to-grave climate change impacts (kg CO_2eq) per functional unit of the bio-SPF$_{MD_CC}$ product for several blowing agents as an alternative for the target blowing agent, methyl formate.

Figure 13 focuses on how the life cycle climate change impacts per *f.u.* changes as the assumed blowing agent methyl formate is replaced with alternative blowing agents. In these results the assumption that these alternative blowing agents can replace methyl formate on a one-to-one mass basis is made. In actuality, less or more of the alternative blowing agent may be required but more detailed sensitivity analysis could not be made here due to a lack of experimental data at this stage in the project. The blowing agents compared in Figure 13 and their associated global warming potential (GWP) 100 year time horizon values (units: kg CO_2eq/kg CO_2) include the following: HFC-134a (GWP = 1430), HFC-245fa (GWP=1030), HFC-356mfc (GWP = 794), HCFC-141b (GWP = 725), HFC-152a (GWP = 124), HCFC-123 (GWP = 77), and CO_2 (GWP = 1). HFC-245fa, in combination with water (the currently predominant medium density SPF blowing agent used in North America), is also a probable blowing agent to be used in the bio-SPF_{MD_CC} product (Kong 2014). If HFC-245fa replaces the assumed methyl formate blowing agent, then the total climate impact per *f.u.* due to the bio-SPF_{MD_CC} product becomes considerably higher: 31 versus 4.6 kg CO_2eq/*f.u.* or greater than 6.6 times more climate change impact.

Benchmark Analysis

Table 14 shows that the main results for the life cycle climate change impacts are quite similar to LCA studies of similar products in literature.

Table 14: Life cycle climate change impact benchmark analysis

Life cycle CO_2eq results from other studies		
	kg CO_2eq	Reference
SPF, cradle-to-gate, per kg	3	Hammond and Jones 2008
FGB, cradle-to-gate, per kg	1.35	Hammond and Jones 2008
SPF, cradle-to-gate, per kg	4.3	Hichier 2007
FGB, cradle-to-gate, per kg	1.49	Kellenberger et al. 2007
SPF cradle-to-grave, per f.u.	3.71	Duije 2012
FGB, cradle-to-grave, per f.u.	1.77	Duije 2012
SPF_{MD_CC}, cradle-to-grave, per f.u.	27.6	SPFA 2013
SPF_{MD_CC}, cradle-to-grave, per f.u.	31.6	Guest 2014
FGB, cradle-to-gate, per kg	2.35	Guest 2014
FGB, cradle-to-grave, per f.u.	3.53	Guest 2014
Life cycle CO_2eq results from this study		
SPF_{MD_CC}, cradle-to-gate, per kg	3.86	
SPF_{MD_CC}, cradle-to-grave, per f.u.	4.59	

The main difference between Guest (2014) and Kellenberger et al. (2007) for the FGB product at FGB production plant (cradle-to-gate) is due to the assumed electricity mix that covers the electricity demand at the FGB production facility. The Kellenberger et al. (2007) study assumed a much cleaner Swiss electricity grid while Guest (2014) assumed a coal and natural gas intensive Alberta electricity grid. The cradle-to-gate results for the bio-SPF_{MD_CC} product in this study (3.86 kg CO_2eq/kg SPF product at plant) are quite close to the results from Hammon and Jones (2008) (3 kg CO_2eq/kg product at plant) and Hichier (2007) (4.3 kg CO_2eq/kg product at plant). Lastly, SPFA (2013) found similar cradle-to-grave results for the SPF_{MD_CC} when compared to this study if the assumed blowing agent is the same (a combination of HFC-245fa and water)—27.6 versus 30.5 kg CO_2eq/*f.u.*

In order to calculate the difference in life cycle climate change impact due to the bio-polyol versus the more conventional fossil-based polyol blend, the same system as described in section 2 is used and the polyol cradle-to-gate product is replaced with a conventional fossil fuel based cradle-to-gate LCI (Hichier 2007). The impact per *f.u.* then increases to 5.62 kg CO_2eq/*f.u.* making the bio-SPF_{MD_CC} product environmentally superior in terms of climate change impact by about 1.0 kg CO_2eq/*f.u.* Additionally, if the bio-SPF_{MD_CC} can finally be commercialized with the methyl formate blowing agent, this product could achieve further reductions to the majority of SPF_{MD_CC} products on the Alberta market which currently relies on both fossil based polyols and the HFC-245fa blowing agent. This difference is estimated to be about 26 kg CO_2eq/*f.u.* These reductions will be used for further results analysis in Stage 3 to follow.

3.2 Stage 2 Results and Analysis

Figure 14 below presents the potential building operational energy and associated GHG savings across the building types and locations. These results are presented in terms of relative space heating savings (%), on-site total energy savings (kWh/m^2/yr) (i.e. per m^2 floor space) and life cycle GHG emissions savings due to the operational building energy savings (kg CO_2eq/m^2/yr).

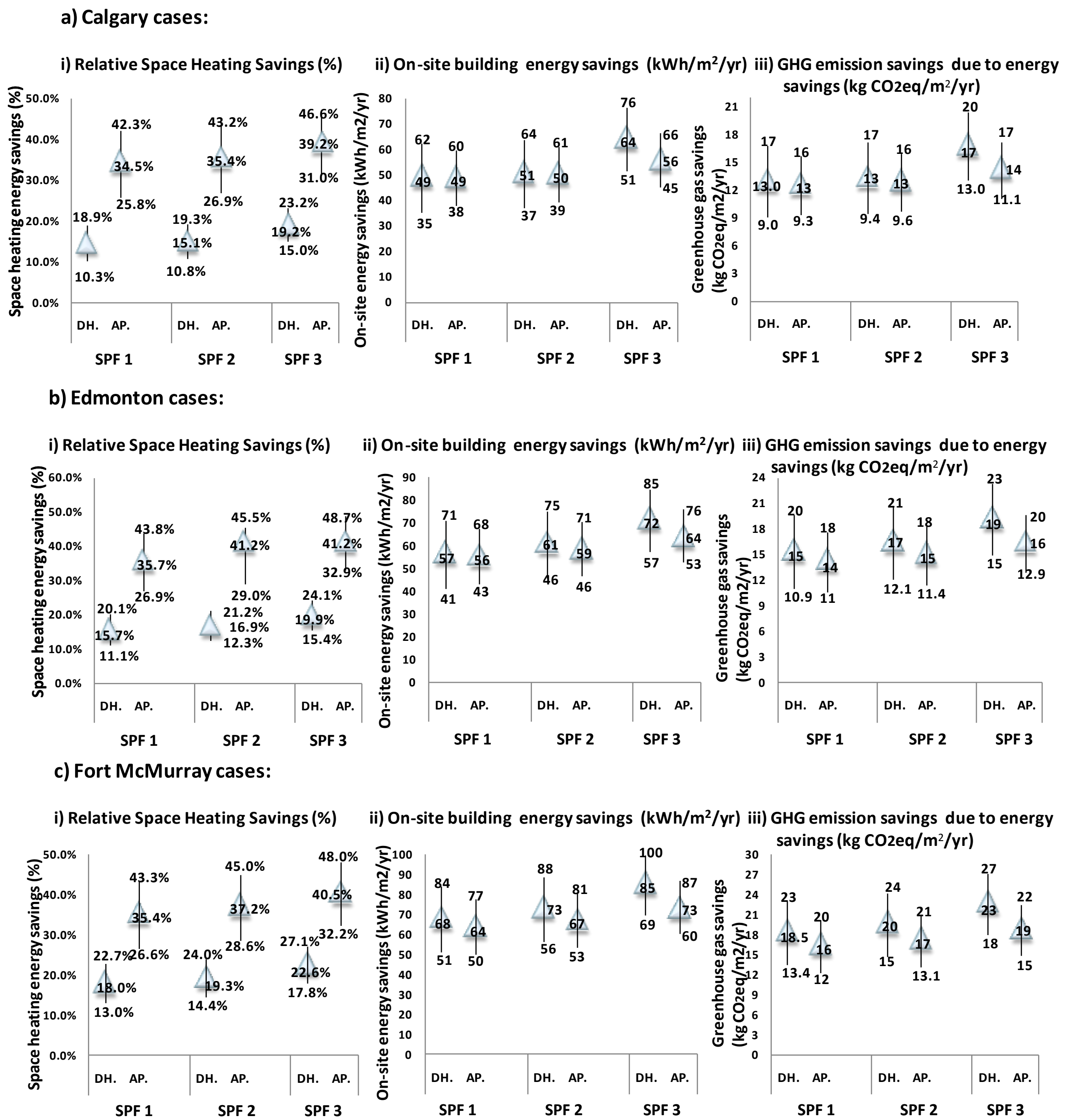


Figure 14: A summary of Stage 2 building simulation energy and GHG savings potential, DH. = detached house, AP. = apartment. SPF 1, 2 and 3 refer to the insulation configuration (see Table 7).

The range of values in Figure 14 are presented as lowest, average, and highest, based on the nine possible savings outcomes (i.e. 3 FGB base case ach specific results versus 3 SPF ach specific results) for each SPF insulation configuration, building and location (see Appendix C for further dissection of these results).

A significant amount of space heating energy requirements can be reduced when SPF insulation is chosen. However, the majority of these energy savings are solely due to the assumptions regarding air infiltration rate measured in air change per house (ach). Since the air infiltration rate of all three SPF configurations is reduced by 2.78 to 6.25 times (i.e. from 0.5-0.75 to 0.12-0.18) when compared to the NECB FGB base cases a considerable drop in energy demand is created. The significant reduction in space heating requirements due to ach value can be observed when comparing the relative savings for the SPF configuration 1 cases to the additional savings when SPF configuration 2 is assumed. Since the same R-value is assumed for roof, wall and floor in the FGB base case and SPF configuration 1, the only difference is due to the air infiltration rates. Subsequent savings relative to SPF configuration 1 are then due to the increase in R_{SI} value of the insulation applied. These results clearly show that the chosen air infiltration rate plays a much larger role in energy reductions than realistic R-values for the insulation.

Provided these ach values are credible across all building types and locations, significant space heating savings are possible. The relative savings range from a low of 10.3% for the Calgary, SPF 1, ach = 0.18 case to a high of 49% for the Edmonton, SPF 3, ach = 0.12 case.

Focusing on the Figure 14, i) sub-plots, a significant disparity can be observed when comparing the relative space heating savings across the two building types simulated—detached house and apartment. This is largely attributed to the building geometry and the importance of convective versus conductive thermal losses. The volume-to-envelope area ratios differ greatly between the buildings: 3.3 for apartment, and 1.26 for detached house. It becomes evident that for a building with greater volume-to-envelope area ratio the natural air infiltration rate (convective heat transfer) will play a bigger role than heat transfer through the solid layers of the envelope (conductive heat transfer). Since the ach values are the same across the two building types, the significant energy demand reduction from FGB base case to SPF configurations creates the greatest relative savings for the largest building. Additionally, since inside air needs to travel over less distance before contacting the building boundary it is sensible that conductive heat transfer plays a more influential role on the relative savings, and as noted earlier, additional insulation (increasing R-value) is not as influential as natural air infiltration rate given the range of values used in this analysis.

However, when focusing on the absolute energy/GHG savings on a per m^2 floor-space basis as is shown in the figure 14, ii) and iii) sub-plots, the detached house is found to have the highest savings rather than the apartment building. This is mostly due to the detached house being less energy efficient on a per m^2 floor-space basis.

In Table 15 the GHG payback periods are presented when both the methyl formate/water and HFC-245fa/water blowing agents are assumed to be used. The life cycle GHGs per *f.u.* (in stage 1) used in this analysis are the following: 4.59 kg CO_2eq/*f.u.* (bio-SPF$_{MD_CC}$ with methyl formate), 30.5 kg CO_2eq/*f.u.* (bio-SPF$_{MD_CC}$ with HFC-245fa) and 2.53 kg CO_2eq/*f.u.*(FGB).

Table 15: GHG payback periods (years) for the various building simulations

a) The apartment building simulations

	For the bio-SPF$_{MD_CC}$ with methyl hydrate blowing agent				For the bio-SPF$_{MD_CC}$ with HFC-245fa blowing agent		
	Calgary cases				**Calgary cases**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.21	0.22	0.23	SPF config. 1	5.25	7.34	10.34
SPF config.2	0.27	0.28	0.47	SPF config.2	5.59	7.74	11.50
SPF config. 3	0.43	0.45	0.50	SPF config. 3	6.37	8.53	12.07
	Edmonton cases				**Edmonton cases**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.22	0.23	0.24	SPF config. 1	5.54	7.74	10.92
SPF config.2	0.31	0.33	0.34	SPF config.2	6.01	8.26	11.44
SPF config. 3	0.46	0.48	0.50	SPF config. 3	6.72	8.98	12.07
	Fort McMurray				**Fort McMurray**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.19	0.20	0.21	SPF config. 1	4.83	6.75	9.52
SPF config.2	0.27	0.29	0.30	SPF config.2	5.25	7.21	9.99
SPF config. 3	0.40	0.42	0.44	SPF config. 3	5.88	7.87	10.60

b) The detached house simulations

	For the bio-SPF$_{MD_CC}$ with methyl hydrate blowing agent				For the bio-SPF$_{MD_CC}$ with HFC-245fa blowing agent		
	Calgary cases				**Calgary cases**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.51	0.54	0.56	SPF config. 1	13.01	18.74	27.03
SPF config.2	0.66	0.70	1.04	SPF config.2	13.83	19.69	24.96
SPF config. 3	0.96	1.00	1.11	SPF config. 3	14.31	18.90	26.50
	Edmonton cases				**Edmonton cases**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.52	0.55	0.57	SPF config. 1	13.24	18.83	26.90
SPF config.2	0.73	0.76	0.80	SPF config.2	14.14	19.62	27.32
SPF config. 3	1.03	1.07	1.11	SPF config. 3	15.11	19.99	26.50
	Fort McMurray				**Fort McMurray**		
	Low	Average	High		Low	Average	High
SPF config. 1	0.44	0.46	0.48	SPF config. 1	11.21	15.70	22.08
SPF config.2	0.62	0.64	0.67	SPF config.2	11.98	16.41	22.57
SPF config. 3	0.87	0.91	0.94	SPF config. 3	12.84	16.82	22.11

The GHG payback periods for the bio-SPF$_{MD_CC}$ insulation product are very fast when methyl formate can be used as the primary blowing agent where the high majority of payback periods are less than one year for both the apartment and the detached house. When HFC-245fa is the primary blowing agent in the bio-SPF$_{MD_CC}$ product, the payback periods become significantly longer. For the apartment building the average GHG payback period ranges from 7-9 years and for the detached house this average ranges from 15-20 years. Given a residential building can be maintained for over one-hundred years (Smith et al. 2006) even these high payback periods seem quite reasonable.

3.3 Stage 3 Results and Analysis

Figure 15 and 16 provide province-wide estimates for direct energy and life cycle GHG savings, respectively, for the three SPF insulation market penetration scenarios within the residential sector of Alberta. The energy savings and GHG reductions provided in Stage 2 results (depicted in Figure 14) are used to estimate these benefits for a time period from 2014-2022. Only newly built residential buildings are considered where residential buildings that installed SPF insulation before 2014 are not included in these annual energy savings and GHG reductions potential. The initial 2014 SPF insulation market share within the residential sector of Alberta is estimated to be 5% (own assumption).

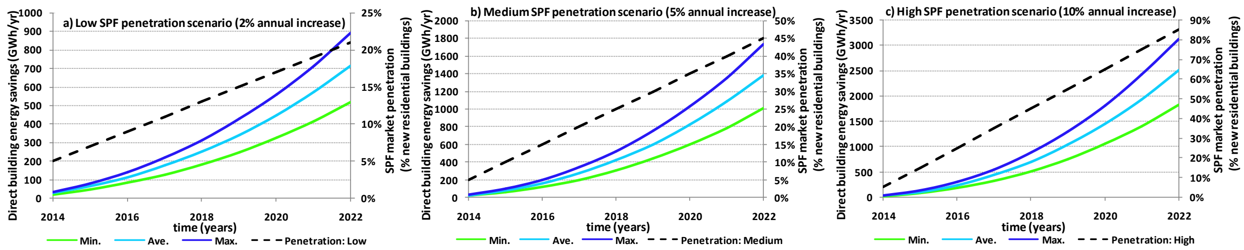


Figure 15: Direct (on-site) operational building energy savings due to the three SPF market penetration scenarios. a) Low penetration (2% increase/yr); b) Medium penetration (5% increase/yr); c) High penetration (10% increase/yr). Min., Ave. and Max. refer to per m² energy savings from Stage 2 results (see Figure 14)

A minimum, average and maximum energy savings and GHG reduction projection is calculated for each of the market penetration scenarios. The difference between these projections is based on the minimum, average and maximum values determined within the Stage 2 results (see Figure 14). By 2022 the energy savings due to SPF insulation market penetration within the residential market of Alberta range from 520-890 GWh/year for the low penetration scenario, 1000-1700 GWh/year for the medium penetration scenario and 1800-3100 GWh/year for the high penetration scenario. To put these numbers in perspective, the total annual energy consumption in the residential sector of Alberta was 57,880 GWh in 2012 (Statistics Canada 2014e).

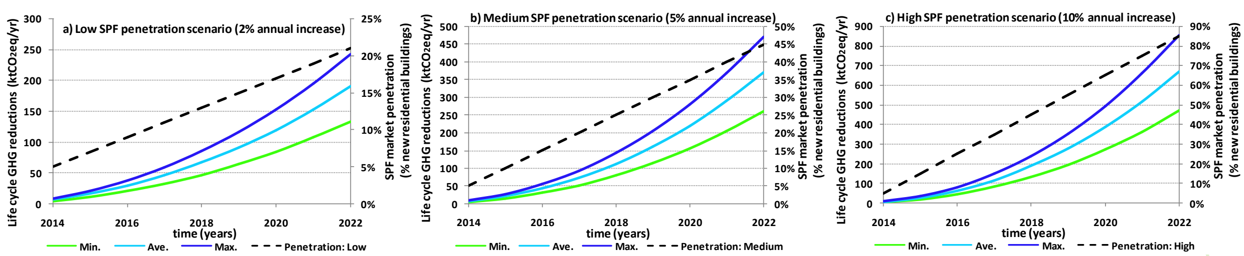


Figure 16: Life cycle GHG emission reductions due to operational building energy savings for the three SPF market penetration scenarios. a) Low penetration (2% increase/yr); b) Medium penetration (5% increase/yr); c) High penetration (10% increase/yr). Min., Ave. and Max. refer to per m² GHG savings from Stage 2 results (see Figure 14)

Similar to the energy savings potential presented in Figure 15, minimum, average and maximum projections of GHG emission reductions are presented for each market penetration scenario. These GHG emission reductions are due to the life cycle GHG emissions associated with the production of the energy demanded by the residential buildings (mainly natural gas for heating). By 2022 the GHG emissions reductions due to SPF insulation market penetration within the residential market of Alberta range from 130-240 kt CO_2eq/year for the low penetration scenario, 260-470 kt CO_2eq/year for the medium penetration scenario and 470-850 kt CO_2eq/year for the high penetration scenario. To put these numbers in perspective, the total annual GHG emissions of Alberta was 249 Mt CO_2eq/year in 2012 (Environment Canada 2014). At the current price on carbon at \$15/tCO_2, offset revenue due to using SPF insulation in the residential building sector could range from \$1,950,000 - \$12,750,000 per year by 2022.

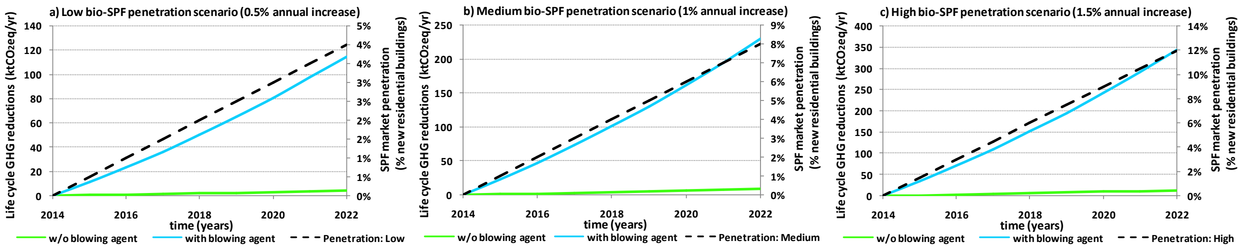


Figure 17: Life cycle GHG emission reductions due to the bio-SPF$_{MD_CC}$ product replacing the currently conventional SPF$_{MD_CC}$ product for three bio-SPF market penetration scenarios. a) Low penetration (0.5% increase/yr); b) Medium penetration (1% increase/yr); c) High penetration (1.5% increase/yr). w/o (without) blowing agent means savings without accounting for impacts due to blowing agent and with blowing agent includes impact due to blowing agent.

In Figure 17 above the GHG emission reductions are due to the life cycle GHG emissions associated with the life cycle cradle-to-grave impacts due to the bio-SPF$_{MD_CC}$ product replacing the conventional SPF$_{MD_CC}$ product on the Alberta market. When the blowing agent is factored out (assuming the bio-SPF$_{MD_CC}$ product using the conventional blowing agent HFC-145fa), the 1.0 kg CO_2eq/*f.u.* GHG savings lead to 4.5, 9.0 and 13.5 kt CO_2eq/year by 2022 for the low, medium and high penetration scenarios, respectively. If the bio-SPF$_{MD_CC}$ product can be commercialized with the methyl formate blowing agent (or a similarly zero GWP blowing agent) and its GHG benefits relative to the conventional HFC-245fa blowing agent are considered, the 26 kg CO_2eq/*f.u.* lead to 114, 230, 340 kt CO_2eq/year by 2022 for the low, medium and high residential market penetration scenarios, respectively. At the current price on carbon at \$15/tCO_2, offset revenue due to using the climate friendlier bio-SPF$_{MD_CC}$ within the residential building sector could range from \$67,500 - \$5,160,000 per year by 2022.

4. Discussion

4.1 Stage 1 analysis

An environmentally friendlier blowing agent is a must

The primary blowing agents considered for the bio-SPF_{MD_CC} product are methyl formate ($GWP_{TH=100}$ = 0) and HFC-245fa ($GWP_{TH=100}$ = 1030) and the off-gassing of this HFC-245fa molecule alone can lead to of ~82% of the total life cycle GHG emissions for this product. HFC-245fa became popularized in North America after the Montreal Protocol called for the elimination of chlorofluorocarbon (CFC) blowing agents (Singh 2004). This switch to HFC-245fa is certainly a step in the right direction as it causes zero ozone layer depletion potential (ODP) and the $GWP_{TH=100}$ of CFC-11 and CFC-12 is 4750 and 10900, respectively, (Forster et al. 2007). Even so, with HFC-245fa having a GWP of 1030 it is essential that effective blowing agents of significantly lower GWP be utilized in closed cell spray foam applications. From this perspective, the methyl formate alternative is one of the best blowing agent options while cyclo-pentane has also shown promising results (Park et al. 2013) with a relatively low $GWP_{TH=100}$ of 7. Other low-GWP blowing agents such as hydrofluorolefins (HFOs) are likely to be available from Honeywell and DuPont in the next few years, though it is unknown how quickly SPF manufacturers could convert to these other compounds (Wilson 2010).

Increases in Canola production: how much is too much?

As the commercial production of herbicide tolerant (HT) canola began in Western Canada in 1997, it has proliferated with a more than 95% adoption rate (Smyth et al. 2011). HT canola allows farmers to avoid or lessen the need for a summer fallow rotation, while simultaneously making no-tillage practices ideal for the canola crop which has also witnessed a high adoption rate in the region leading to considerable environmental benefits (namely increased CO_2 sequestration and reduced herbicide application) (Smyth et al. 2011). On the contrary, canola grown on canola requires roughly twice as much nitrogen fertilizer (36 vs. 76 kg N/ha) which could significantly offset these environmental gains (Shrestha et al. 2014). As Figure 18, a) below shows, the unprecedented growth of canola seeded crop area in Alberta has mostly come at the expense of reduced land area earmarked to summer fallow land and tame hay.

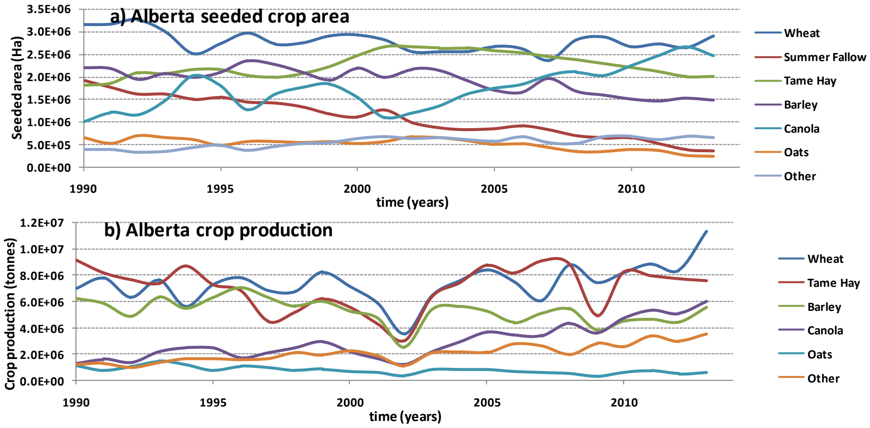


Figure 17: A time series depicting the seeded crop area and crop production in the province of Alberta (Statistics Canada 2014a)

In contrast to the trends in seeded area, annual production of key crops in Alberta have generally continued to increase--apart from the great Canadian coast-to-coast drought of 2001-02 (Agriculture and Agri-Food Canada 2013)--despite slight decreasing trends for the top five crops (besides canola) in terms seeded crop area for wheat, tame hay, barley and oats. This indicates that thus far, increases in canola production have not greatly influenced the other major crops produced in Alberta. It seems likely that to sustain desired increasing trends of canola production the majority of these gains will now need to be made with yield increases and not land expansion (Canola Watch 2014).

4.2 Stage 2/3 analysis

Air infiltration rates – are the numbers used in this analysis credible?

The air leakage rates used in this analysis varied from 0.5 to 0.75 ach for the FGB insulated buildings and from 0.12 to 0.18 ach for the SPF configurations. Typical air infiltration values in housing in North America vary by a factor of about ten, from tightly constructed housing with seasonal average air exchange rates as low as 0.1 ach to loosely constructed buildings with ach rates as great as 2.0 (ASHAE 2009). For instance, Palmiter and Brown (1989) and Parker et al. (1990) found a heating season average of 0.4 ach (range: 0.13to 1.11 ach) for 134 houses in the Pacific Northwest climates. Parker et al. (1990) undertook a comparative study between 292 energy-efficient houses (including air infiltration reduction measures) and 331 control houses. This study found an average of about 0.25 (range: 0.02 to 1.63) for the energy-efficient houses versus 0.49 (range: 0.05to 1.63 ach) for the control. Desrochers and Scott (1985) estimated that building occupancy adds an average of 0.10 to 0.15 ach to unoccupied values while Kvisgaard and Collet (1990) found that in sixteen Danish dwellings occupants on average provided 63%

of the total air exchange rate. According to Sherman and Matson (2002) the average air tightness of all houses in the United States is 1.18 ach while new homes that were built post-1993 had a mean ach of 0.55. Additionally they found that homes that were constructed under some local or national energy-efficient program have a mean ach of 0.31. These studies however, did not differentiate between FGB and SPF insulated building envelopes.

Typical distributions of air leakage rates across building components are as follows: 18-50% through walls (holes/other openings), 3 to 30% through ceiling details, 3 to 28% through forced-air heating/cooling systems, 6-22% through windows and doors, 0 to 30% through fireplaces (if applicable), 2 to 12% through vents in conditioned spaces and less than 1% via diffusion through walls (Dickerhoff et al. 1982; Harrje and Born 1982). Therefore, envelope insulation and its effectiveness at eliminating cracks and holes can play a significant role in the overall air infiltration rate.

There have been some studies that directly measure air infiltration between envelopes that were insulated with FGB and/or SPF (or a similar product) (NAHB 2007; NAHB 2009; SPC 2010). NAHB (2007) used a dataset of fifty-six homes from thirteen U.S. states that had applied icynene spray foam that had been tested for air tightness. They found that the average natural air infiltration was 0.10 ach and the distribution was fairly tight with the standard deviation ranging from 0.06 to 0.14 ach. Icynene spray foam is similar to a light density SPF and therefore the results from NAHB (2007) are relatively transferrable to this analysis and even lower ach values could be achieve with the denser bio-SPF_{MD_CC} product. NAHB (2007) quite clearly illustrated that spray foam can achieve the ach range that is used for the SPF configurations in this analysis where the average that they found was slightly lower than the minimum ach value used in this study (0.10 versus 0.12).

SPC (2010) underwent a side-by-side comparison of three identically constructed homes in South Texas. The first home used R-30 blown in fiberglass on the attic floor, and R-13 FGB batt for the wall cavities. The second home used R-28 open cell SPF under the roof deck while the exterior wall was filled with R-15 FGB and R-3 sheathing. Lastly, the third house used the same R-28 open SPF roof insulation, and in the walls used R-12 open cell SPF along with R-4 sheathing. Using a blower door apparatus the air leakage of each home was measured and recorded as ach at 50 Pascal pressure difference (ach_{50}) between the inside and outside of the building. The first home had a measured leakage of 5.84 ach_{50}, while the second and third homes had ach_{50} values of 3.64 and 1.95. There is almost a factor-of-three change in ach value between the first home that only used FGB and the last home that only used the SPF insulation. These significant differences are also supportive of the ach values chosen for this study. SPC (2010) also performed a modeling analysis of these homes in order to isolate the building energy savings due to the SPF insulation. They modelled these homes in both Texas and the much cooler climate of

Richmond, Virginia finding that 21% and 22% annual energy consumption could be saved (home 3 compared to home 1). These relative savings are in close agreement with the results presented in this analysis (see Figure 14).

Can carbon offsets realistically be granted for SPF insulated buildings?

Currently Alberta has a GHG protocol for energy efficiency measures (EEM) focused within commercial and institutional buildings (Government of Alberta 2010), but at this point in time nothing exists for residential buildings. This is likely due to individual housing units or apartment buildings attaining too few carbon offsets per building to make the carbon offset application worthwhile. However, if a large number of projects can be pooled together in a GHG offset application then the prospects of EEMs in the residential sector could potentially become more lucrative. A GHG protocol covering EEMs within the residential sector would most likely follow the same or very similar rulings as the current building EEM protocol actualized today. Therefore, it is informative to question whether SPF insulation can adequately be proven to be an EEM that is a justifiable GHG offset in the Alberta market.

The current protocol for commercial and institutional buildings requires the baseline system to meet up-to-date NECB standards and quantified energy savings would likely need to be determined with a calibrated building simulation that clearly proves the SPF insulation leads to significant savings relative to the FGB baseline. Greater proof through empirical measurements of natural air infiltration rates for at least the first few GHG offset applications will also likely be required.

Another carbon offset issue of concern for the SPF insulation EEM is whether the product can adequately be proven that it is indeed an EEM that replaces a baseline system. FGB insulation can arguably be considered as a baseline since it currently dominates the residential sector of Alberta and it is significantly cheaper on a per rated thermal resistance basis when compared to the SPF alternative. But how many years into the future can the FBG insulation option be considered as the baseline alternative?

Concluding Remarks

The results of this analysis indicate that the bio-SPF_{MD_CC} product under development is a promising alternative to the more conventional SPF and FGB insulation alternatives. It is essential that a low GWP blowing agent be made to work in this product while ensuring that desirable insulation properties are still maintained. Despite the likelihood that the bio-SPF_{MD_CC} product creates higher climate change impact per f.u., than its FGB insulation counterpart, the ability for the SPF product to significantly reduce operational building energy demand allows for a very short GHG payback period leading to significant GHG reductions throughout the life time of the building. If the adoption rate of SPF insulation continues to grow in Alberta, then substantial carbon offsets should be justified. However, this will be challenging given the relatively small GHG savings per building. There is a need to efficiently pool SPF insulation related building projects together when applying for GHG credits. The transaction costs that go into proving SPF related GHG savings are likely to be an initial obstacle that could be overcome provided the verification scheme can become fairly automated. Certainly more empirical research is required in order to guarantee that such energy savings and GHG reductions are realistic. Given these preliminary results, the SPF insulation product is an environmentally superior product and it should be promoted and widely adopted.

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Appendix A. Stage 1 Gate-to-Gate Life Cycle Inventories

The following tables provide gate-to-gate input/output life cycle inventory that was used in this analysis. The ID# refers to the identification number of the main foreground processes in the value chain of the bio-SPF product. These main processes are interlinked with the Ecoinvent v2.2 database as a background system. In this background system is where the majority of processes and emission information resides. Therefore, for greater details into the gate-to-gate inventory one should have ready access to the Ecoinvent v2.2 database (Ecoinvent 2014).

ID#		value	unit	source
10001	**SPF Use and Maintenance**	1	f.u.	
	Inputs from technosphere:			
10002	*SPF End-of-Life Treatment*	1.07	kg	own assumption
10003	*SPF Installation*	1.00	unit	own assumption
10004	*Fresh SPF waste disposal*	0.044	kg	own assumption
10005	*Transport: SPF to Construction Site*	0.12	tkm	own assumption
10006	*SPF Regional Storage*	1.17	kg	own assumption
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10002	**SPF End-of-Life Treatment**	1	kg	
	Inputs from technosphere:			
	disposal, polyurethane, 0.2% water, to inert material landfill/ CH/ kg	1	kg	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10003	**SPF Installation**	1	pc	
	Inputs from technosphere:			
	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	0.02	MJ	ecoinvent v2.2
	Stressors on environment:			
	carbon dioxide, fossil, air, low population density, kg	0.0287	kg	SPFA 2013
	-- for other stressors follow process/source for more info --			

ID#		value	unit	source
10004	**Fresh SPF waste disposal**	1	kg	
	Inputs from technosphere:			
	disposal, polyurethane, 0.2% water, to inert material landfill/ CH/ kg	1	kg	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10005	**Transport: SPF to Construction Site**	1	tkm	
	Inputs from technosphere:			
	transport, lorry 7.5-16t, EURO5/ RER/ tkm	1	tkm	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10006	**SPF Regional Storage**	1	kg	
	Inputs from technosphere:			
10007	*Transport: SPF plant to regional storage*	0.015	tkm	own assumption
10008	SPF Production at mixing plant	1	kg	own assumption
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10007	**Transport: SPF plant to regional storage**	1	tkm	
	Inputs from technosphere:			
	transport, lorry >16t, fleet average/ RER/ tkm	1	tkm	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10008	**SPF Production at mixing plant**	1	kg	
	Inputs from technosphere:			
10009	*Electricity: Requirements at SPF production plant*	0.417	kWh	ecoinvent v2.2
10010	*Heating: Requirements at SPF production plant*	0.2	MJ	own assumption
10011	*Biopolyol production, at plant*	0.375	kg	SPFA 2013
10015	*Diisocyanate production mix*	0.5	kg	SPFA 2013
10016	*Blowing agent*	0.0525	kg	SPFA 2013
10017	*Catalyst*	0.0175	kg	SPFA 2013
10018	*Flame Retardant*	0.05	kg	SPFA 2013
10019	*Surfactant*	0.0025	kg	SPFA 2013
10020	*Infrastructure, SPF plant*	4E-10	pc	ecoinvent v2.2
10021	*Transport: biopolyol from plant to SPF preparation*	0.0075	tkm	own assumption
10022	*Transport: Diisocyanate mix*	1.8465	tkm	own assumption
10023	*Transport: Catalyst*	0.00875	tkm	own assumption
10024	*Transport: Blowing agent*	0.02625	tkm	own assumption
10025	*Transport: Flame Retardant*	0.0625	tkm	own assumption
10026	*Transport: Surfactant*	0.00125	tkm	own assumption
	disposal, polyurethane, 0.2% water, to municipal incineration/ CH/ kg	0.02	kg	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10009	**Electricity: Requirements at SPF production plant**	1	kWh	
	Inputs from technosphere, process name:			
10036	Electricity: Alberta Mix	1	kWh	own assumption
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10010	**Heating: Requirements at SPF production plant**	1	MJ	
	Inputs from technosphere, process name:			
	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	1	MJ	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10011	**Biopolyol production, at plant**	1	kg	
10027	*Inputs from technosphere, process name:*			
*	[redacted] Confidential information			
	chemical plant, organics/ RER/ unit	4E-10	pc	own assumption, ecoinvent v2.2
10012	*Electricity: Requirements for Polyol Production*	0.414	kWh	Omni-Tech International 2010
10013	*Heating: Requirements at biopolyol production plant*	2.22	MJ	Omni-Tech International 2010
10014	*Transport: Canola oil to biopolyol plant*	0.02	tkm	own assumption
**	*transport, lorry >16t, fleet average/ RER/ tkm*	0.55	tkm	own assumption, ecoinvent v2.2
	**used as a proxy, should be 1,3-propanediol; **transport of other main material inputs*			
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10012	**Electricity: Requirements for Polyol Production**	1	kWh	
	Inputs from technosphere, process name:			
10036	Electricity: Alberta Mix	1	kWh	own assumption
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10013	**Heating: Requirements at biopolyol production plant**	1	MJ	
	Inputs from technosphere, process name:			
	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	1	MJ	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10014	**Transport: Canola oil to biopolyol plant**	1	MJ	
	Inputs from technosphere, process name:			
	transport, lorry >16t, fleet average/ RER/ tkm	1	tkm	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10015	**Diisocyanate production mix**	1	kg	
	Inputs from technosphere, process name:			
	methylene diphenyl diisocyanate, at plant/ RER/ kg	1	kg	ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10016	**Blowing agent**	1	kg	
	Inputs from technosphere, process name:			
	methyl formate, at plant/ RER/ kg	0.809524	kg	own assumption, ecoinvent v2.2
	water, ultrapure, at plant/ GLO/ kg	0.190476	kg	own assumption, ecoinvent v2.3
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10017	**Catalyst**	1	kg	
	Inputs from technosphere, process name:			
*	triethanolamine, at plant/ RER/ kg	1	kg	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

**used as a proxy for polycat 5/8 as according to Kong (2014)*

ID#		value	unit	source
10018	**Flame Retardant**	1	kg	
	Inputs from technosphere, process name:			
	propylene oxide, liquid, at plant/ RER/ kg	0.5599	kg	own assumption, ecoinvent v2.2
	phosphorous chloride, at plant/ RER/ kg	0.464	kg	own assumption, ecoinvent v2.2
	oxygen, liquid, at plant/ RER/ kg	0.054	kg	own assumption, ecoinvent v2.2
	chemical plant, organics/ RER/ unit	4E-10	pc	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

**Assumed main chemical inputs for fire retardant TCPP as according to mass balance and 95% yield efficiency*

ID#		value	unit	source
10019	**Surfactant**	1	kg	
	Inputs from technosphere, process name:			
*	silicone product, at plant/ RER/ kg	1	kg	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

**used as proxy for silicone surfactant as according to Kong (2014)*

ID#		value	unit	source
10020	**Infrastructure, SPF plant**	1	pc	
	Inputs from technosphere, process name:			
	chemical plant, organics/ RER/ unit	1	pc	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10021-26	**Transport: inputs to SPF preparation**	1	tkm	
	Inputs from technosphere, process name:			
	transport, lorry >16t, fleet average/ RER/ tkm	1	tkm	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10027	**Canola Oil Crushing/Refining**	1	tkm	
	Inputs from technosphere, process name:			
	phosphoric acid, industrial grade, 85% in H2O, at plant/ RER/ kg	0.000646	kg	econinvent v2.2
	hexane, at plant/ RER/ kg	0.002	kg	econinvent v2.2
	bentonite, at processing/ DE/ kg	0.004269	kg	econinvent v2.2
	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	1.289662	MJ	econinvent v2.2
	treatment, sewage, from residence, to wastewater treatment, class 2/ C	4.92E-06	m3	econinvent v2.2
	oil mill/ CH/ unit	6.07E-10	unit	econinvent v2.2
10028	*Electricity: Requirements for seed crushing/oil refining*	0.081412	kWh	econinvent v2.3
10029	*Transport: Canola seeds to crushing/refining plant*	0.455576	tkm	own assumption
10030	*Canola production*	1.822303	kg	own assumption
	Stressors on environment:			
	hexane, air, high population density, kg	0.002092	kg	ecoinvent v2.2
	carbon dioxide, biogenic, air, high population density, kg	2.28092	kg	ecoinvent v2.2
	heat, waste, air, high population density, MJ	0.910133	MJ	ecoinvent v2.2
	-- for other stressors follow process/source for more info --			

ID#		value	unit	source
10028	**Electricity: Requirements for seed crushing/oil refining**	1	kWh	
	Inputs from technosphere, process name:			
10036	Electricity: Alberta Mix	1	kWh	own assumption
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10029	**Transport: Canola seeds to crushing/refining plant**	1	tkm	
	Inputs from technosphere, process name:			
	transport, lorry >16t, fleet average/ RER/ tkm	0.5	tkm	own assumption, ecoinvent v2.2
	transport, freight, rail/ RER/ tkm	0.5	tkm	own assumption, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

ID#		value	unit	source
10030	**Canola production**	1	kg	
	Inputs from technosphere, process name:			
	rape seed IP, at regional storehouse/ CH/ kg	0.0084	kg	Canola Council 2001, ecoinvent v2.2
	ammonium sulphate, as N, at regional storehouse/ RER/ kg	0.003506	kg	Canola Council 2001, ecoinvent v2.2
	ammonia, liquid, at regional storehouse/ RER/ kg	0.01358	kg	Canola Council 2001, ecoinvent v2.2
	urea ammonium nitrate, as N, at regional storehouse/ RER/ kg	0.00515	kg	Canola Council 2001, ecoinvent v2.2
	urea, as N, at regional storehouse/ RER/ kg	0.026464	kg	Canola Council 2001, ecoinvent v2.2
	single superphosphate, as P2O5, at regional storehouse/ RER/ kg	0.00855	kg	Canola Council 2001, ecoinvent v2.2
	triple superphosphate, as P2O5, at regional storehouse/ RER/ kg	0.00855	kg	Canola Council 2001, ecoinvent v2.2
	potassium chloride, as K2O, at regional storehouse/ RER/ kg	0.002	kg	Canola Council 2001, ecoinvent v2.2
	potassium nitrate, as K2O, at regional storehouse/ RER/ kg	0.002	kg	Canola Council 2001, ecoinvent v2.2
	lime, from carbonation, at regional storehouse/ CH/ kg	0.293	kg	ecoinvent v2.2
	benzimidazole-compounds, at regional storehouse/ RER/ kg (fungicide	9.08E-06	kg	ecoinvent v2.2
	cyclic N-compounds, at regional storehouse/ RER/ kg	2.31E-05	kg	ecoinvent v2.2
	glyphosate, at regional storehouse/ RER/ kg (herbicide)	0.000199	kg	Smyth et al. 2011, ecoinvent v2.2
	pesticide unspecified, at regional storehouse/ RER/ kg	0.000212	kg	ecoinvent v2.2
	phenoxy-compounds, at regional storehouse/ RER/ kg (2,4-D - herbici	5.84E-06	kg	Smyth et al. 2011, ecoinvent v2.2
	pyretroid-compounds, at regional storehouse/ CH/ kg (insecticide)	2.47E-05	kg	ecoinvent v2.2
	transport, lorry 20-28t, fleet average/ CH/ tkm	0.05053	tkm	ecoinvent v2.2
	transport, barge/ RER/ tkm	0.28581	tkm	ecoinvent v2.2
	transport, freight, rail/ RER/ tkm	0.05053	tkm	ecoinvent v2.2
	application of plant protection products, by field sprayer/ CH/ ha	0.000633	ha	ecoinvent v2.2
	combine harvesting/ CH/ ha	0.000145	ha	ecoinvent v2.2
	fertilising, by broadcaster/ CH/ ha	0.000318	ha	ecoinvent v2.2
	grain drying, low temperature/ CH/ kg	0.068182	ha	ecoinvent v2.2
	sowing/ CH/ ha	0.000218	ha	ecoinvent v2.2
	transport, tractor and trailer/ CH/ tkm	0.0150	tkm	ecoinvent v2.2
	Stressors on environment:			
	pb, soil, agricultural, kg	2.78E-06	kg	ecoinvent v2.2
	zinc, soil, agricultural, kg	6.87E-05	kg	ecoinvent v2.2
	nitrate, water, ground-, kg	3.45E-02	kg	ecoinvent v2.2
	metazachlor, soil, agricultural, kg	1.39E-04	kg	ecoinvent v2.2
	nitrous oxide, air, low population density, kg	4.05E-04	kg	S & T 2010
	trinexapac-ethyl, soil, agricultural, kg	1.87E-07	kg	ecoinvent v2.2
	fluazifop-p-butyl, soil, agricultural, kg	3.24E-06	kg	ecoinvent v2.2
	deltamethrin, soil, agricultural, kg	5.38E-07	kg	ecoinvent v2.2
	napropamide, soil, agricultural, kg	1.04E-05	kg	ecoinvent v2.2
	phosphorus, water, ground-, kg	2.05E-05	kg	ecoinvent v2.2
	white phosphorus, water, river, kg	1.19E-04	kg	ecoinvent v2.2
	clomazone, soil, agricultural, kg	3.17E-07	kg	ecoinvent v2.2
	cadmium, soil, agricultural, kg	5.29E-07	kg	ecoinvent v2.2
	cu, soil, agricultural, kg	3.10E-06	kg	ecoinvent v2.2
	chlormequat, soil, agricultural, kg	3.77E-05	kg	ecoinvent v2.2
	nickel, soil, agricultural, kg	2.91E-06	kg	ecoinvent v2.2
	2,4-d, soil, agricultural, kg	5.08E-06	kg	ecoinvent v2.2
	carbon dioxide, resource, in air, kg	2.69E+00	kg	ecoinvent v2.2
	propaquizafop, soil, agricultural, kg	7.52E-06	kg	ecoinvent v2.2
	tebuconazole, soil, agricultural, kg	1.63E-05	kg	ecoinvent v2.2
	prochloraz, soil, agricultural, kg	1.40E-06	kg	ecoinvent v2.2
	carbendazim, soil, agricultural, kg	9.08E-06	kg	ecoinvent v2.2
	cr, soil, agricultural, kg	1.20E-05	kg	ecoinvent v2.2
	lambda-cyhalothrin, soil, agricultural, kg	3.77E-07	kg	ecoinvent v2.2
	nox to air, air, low population density, kg	3.56E-04	kg	ecoinvent v2.2
	carbon dioxide, fossil, air, low population density, kg	1.07E-02	kg	ecoinvent v2.2
	carbon dioxide, soil organic carbon, kg	-1.1E+00	kg	West and Post 2002
	trifluralin, soil, agricultural, kg	2.39E-05	kg	ecoinvent v2.2
	glyphosate, soil, agricultural, kg	4.11E-05	kg	ecoinvent v2.2
	cypermethrin, soil, agricultural, kg	2.57E-05	kg	ecoinvent v2.2
	ammonia, air, low population density, kg	2.40E-03	kg	ecoinvent v2.2
	transformation, from pasture and meadow, resource, land, m2	8.50E-01	m2	ecoinvent v2.2
	transformation, from arable, non-irrigated, resource, land, m2	2.08E+00	m2	ecoinvent v2.2
	transformation, to arable, non-irrigated, resource, land, m2	2.93E+00	m2	ecoinvent v2.2
	occupation, arable, non-irrigated, resource, land, m2a	2.69E+00	m2a	ecoinvent v2.2
	metconazole, soil, agricultural, kg	5.07E-06	kg	ecoinvent v2.2
	energy, gross calorific value, in biomass, resource, biotic, MJ	2.78E+01	MJ	ecoinvent v2.2
	-- for other stressors follow process/source for more info --			

ID#		value	unit	source
10036	**Electricity: Alberta Mix**	1	kWh	
	Inputs from technosphere, process name:			
	electricity, natural gas, at power plant/ US/ kWh	0.232169	kWh	NEB 2013, ecoinvent v2.2
	electricity, hard coal, at power plant/ US/ kWh	0.640385	kWh	NEB 2013, ecoinvent v2.2
	electricity, hydropower, at power plant/ DE/ kWh	0.198157	kWh	NEB 2013, ecoinvent v2.2
	electricity, at wind power plant/ RER/ kWh	0.029288	kWh	NEB 2013, ecoinvent v2.2
	Stressors on environment:			
	-- follow process/source for more info --			

Appendix B. Stage 1: Other Environmental Impact Results

Figure B1 below provides the same breakdown as Figure 9 but considers four other important environmental impact categories: fossil (fuel) depletion (units: kg oil eq), metal depletion (units: kg Fe (iron) eq), terrestrial acidification (units: kg SO_2eq (sulphur dioxide)) and human toxicity (units: kg 1,4-DBeq (dichlorobenzene)).

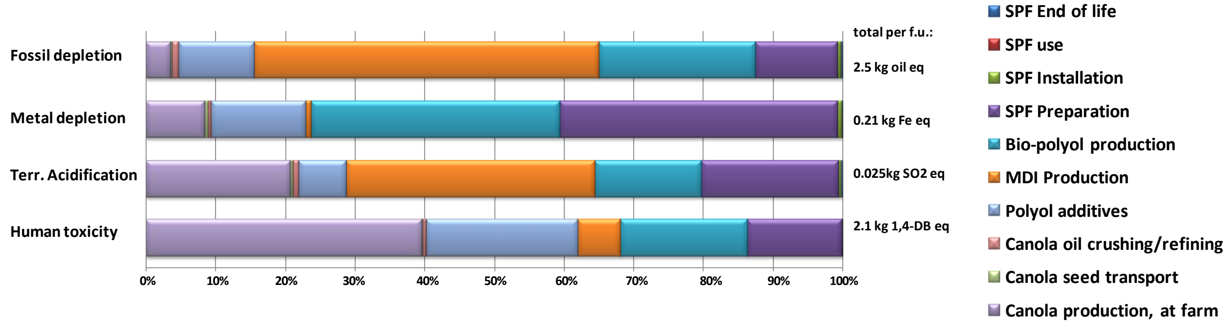

Figure B1: Cradle-to-grave environmental impacts for several other important impact categories due to each foreground process (direct + indirect) per functional unit. Terr.= terrestrial, 1,4-DB= 1,4-Dichlorobenzene.

Figure B2 below provides an aggregated look at the total environmental impact for the eighteen midpoint impact categories covered in the ReCiPe 2008 methodology (Goedkoop et al. 2012).

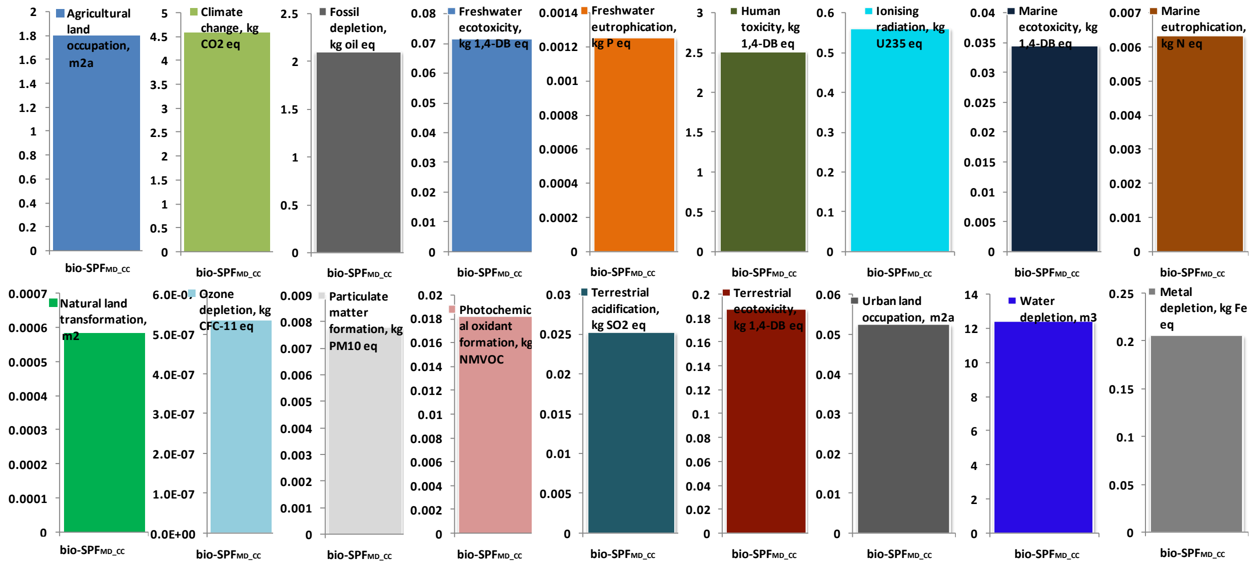

Figure B2: Total Cradle-to-grave environmental impacts for several midpoint impact categories due to the bio-SPF$_{MD_CC}$ product and on a per f.u. basis.

Appendix C. Stage 2 Building simulation figures

The following figures provide greater details into the Stage 2 results. The figures to follow were used to generate the main summarized results as presented in the results section in Figure 14.

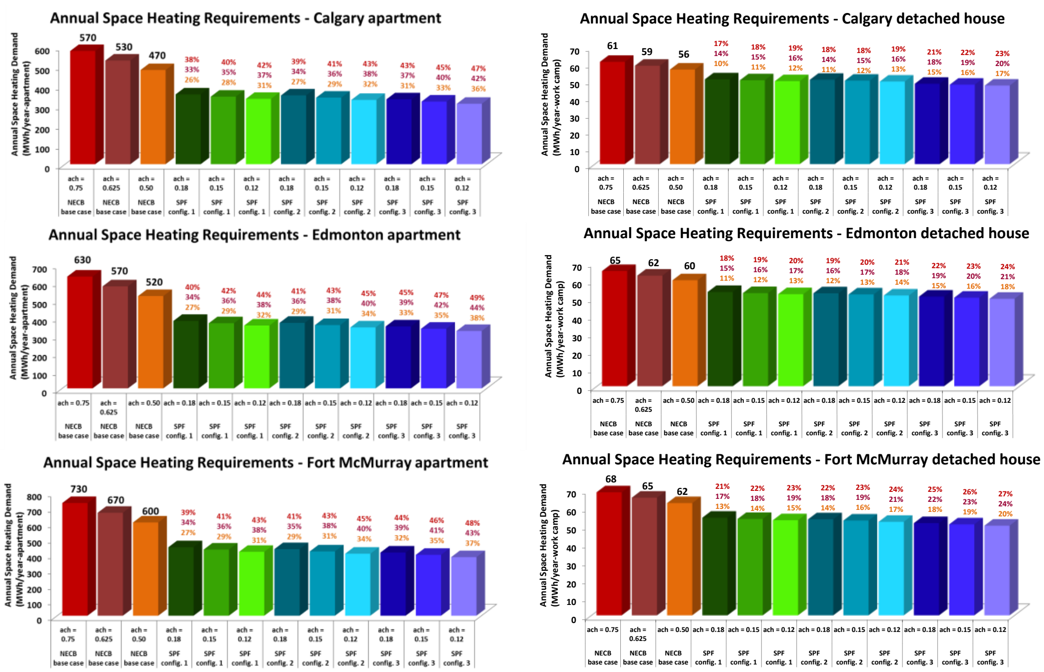

Figure C1: Apartment (left) and detach house (right) annual operational space heating requirements for the NECB compliant and proposed SPF configurations when natural gas furnace space heating is assumed. Percentages are savings relative to the NECB compliant FGB base cases and color coded accordingly.

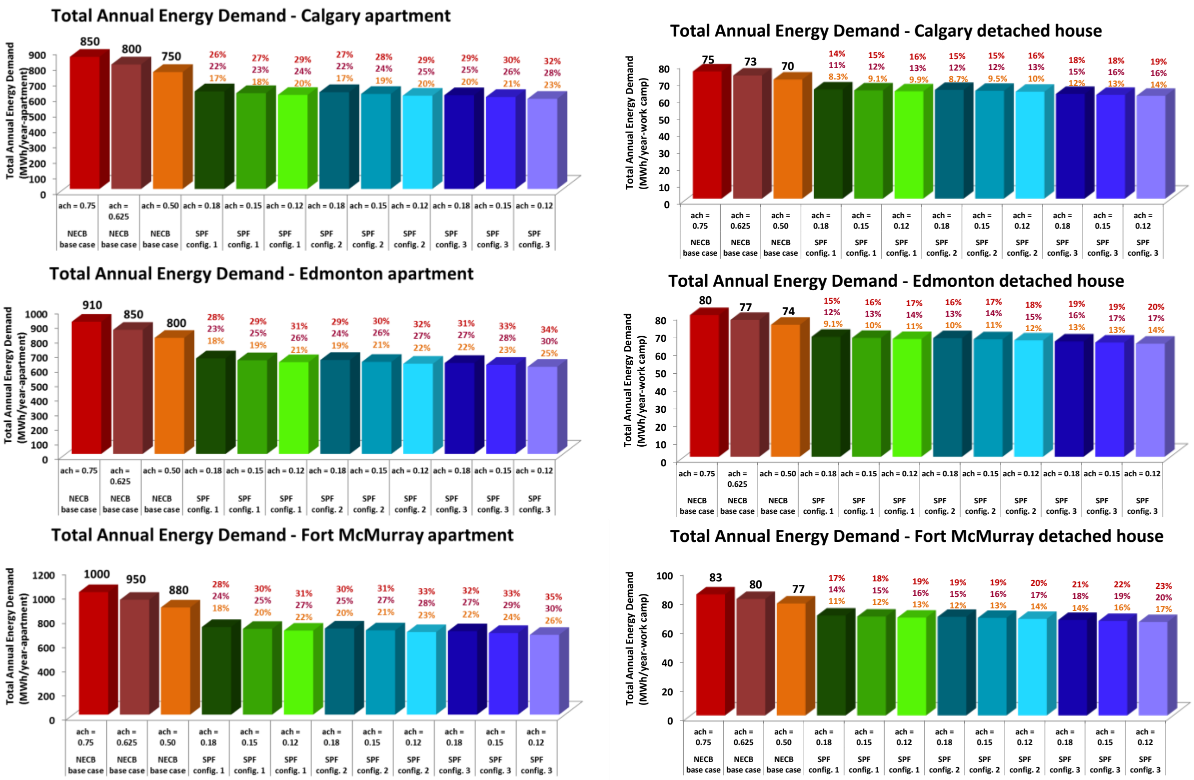

Figure C2: Apartment (left) and detached house (right) total operational energy requirements for the NECB compliant and proposed SPF configurations when natural gas furnace space heating is assumed. Percentages are savings relative to the NECB FGB compliant base cases and color coded accordingly.

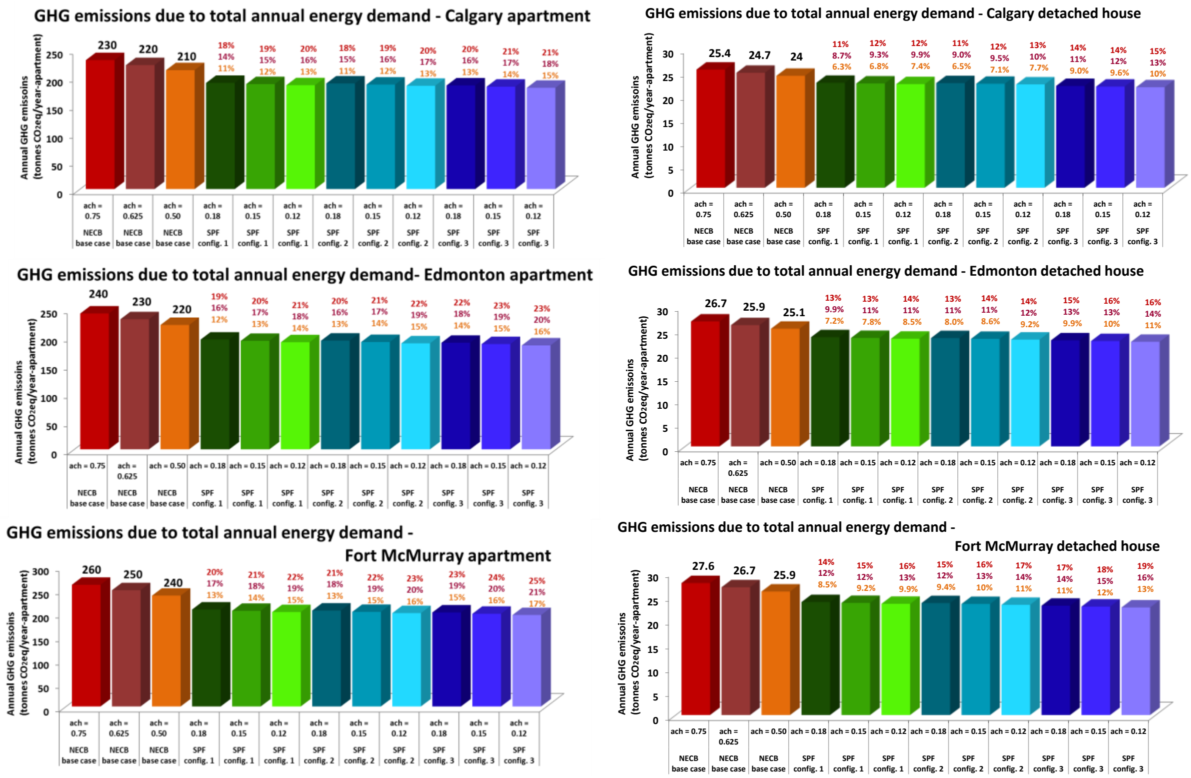

Figure C3: Apartment (left) and detached house (right) annual life cycle GHG emissions due to total operational energy requirements for the NECB compliant and proposed SPF configurations when natural gas furnace space heating is assumed. Percentages are savings relative to the NECB compliant FGB base cases and color coded accordingly.