RESEARCH HIGHLIGHT

A Life-Cycle Environmental Assessment Benchmark Study of Six CMHC EQuilibrium™ Housing Initiative Projects

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INTRODUCTION

In 2006, Canada Mortgage and Housing Corporation (CMHC) launched a "Net-Zero Energy[1] Healthy Housing" demonstration project that came to be known as the EQuilibrium™ (EQ) Sustainable Housing Demonstration Initiative. The objective of the initiative was to support leading builders to plan, design, construct, demonstrate and monitor new models for the next generation of sustainable housing in Canada. While the net-zero annual energy consumption target was relatively well understood in terms of impact on annual operating energy use, what was not immediately apparent was how much more energy would have to be embodied in each of the houses over a given life-cycle period to meet such a high performance objective and what the related environmental impacts would be.

To gain a better understanding of this research question, CMHC engaged the Athena Sustainable Materials Institute to undertake a 20-year life-cycle assessment (LCA) of the designs of six EQuilibrium houses to estimate and evaluate the environmental performance and inherent trade-offs associated with achieving net-zero annual energy consumption. This was compared to the energy and environmental impacts associated with more conventional and advanced housing methods that would be expected to have less embodied energy and lower environmental impacts associated with their delivery to construction. The LCA study can best be characterized as a "cradle-to-gate" assessment, where the "cradle" is the earth (all material and energy systems are followed back to the earth) and the "gate" is the completed dwelling and its operation at the end of a predetermined period of time—in this case 20 years. The study quantified the energy and environmental impacts associated with the resource extraction, processing, product manufacturing, delivery, construction, operation and maintenance of the six projects to assess the relative benefits of achieving low operating energy performance given the higher anticipated energy inputs and environmental impacts over the selected 20-year life-cycle.

METHODOLOGY

This research project assessed the designs of six of the eleven EQuilibrium projects constructed under the Initiative. Five projects were new builds and one was a retrofit. Using a holistic LCA framework, the study determined the embodied and operating effects (energy consumed and emissions to the environment produced) of these dwellings relative to more conventional minimum code baselines (as defined in the 2006 Ontario Building Code [OBC]) and more advanced housing options (based on the Natural Resources Canada R-2000 standard, 2005 edition) across a comprehensive set of environmental impact indicators.

[1] For the purpose of this study, "net-zero energy" means that, over the course of a year, a house is capable of producing the same amount of energy or more than it consumes in that same year.

The study scope included the embodied effects considered over the first 20 years[2] of each dwelling's service life. The effects were evaluated within life-cycle activity stages as follows:

- **Manufacturing:** effects related to primary resource harvesting and mining, manufacturing of materials into products, and transportation associated with these activities.
- **Construction:** effects related to finished product transportation to site, and on-site construction energy use and solid waste.
- **Maintenance:** effects related to replacing and maintaining construction assemblies during dwelling use (that is, study period or dwelling service life), also known as "recurring embodied effects."
- **Building service systems:** manufacturing, construction and maintenance stage effects related to electrical, plumbing, heating, ventilation and air-conditioning, energy recovery, and on-site energy production system components.
- **Operating energy:** net effects related to on-site energy use and energy production. The operating energy stage includes space heating and cooling and use of domestic hot water, appliances, lighting, fans and other mechanical systems. On-site energy production includes generation from photovoltaic arrays, solar thermal systems, and energy recovery systems.

The manufacturing, construction and maintenance stages are together the cradle-to-gate embodied effects of the structure and envelope materials. While not specifically a life-cycle stage, the "building service systems" effects were segregated from those associated with the manufacturing, construction and maintenance activity stages. This was done in order to highlight these findings specifically in terms of the mechanical and electrical services since [1] they do not typically appear in dwelling assessments given the lack of publicly available data and [2] these components are of particular importance in terms of their influence on EQuilibrium house baseline performance.

The life-cycle impact indicators selected and used in the study were those supported by the Athena Institute's *Impact Estimator for Buildings* software and based on the United States Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methodology, thus providing a North American context for the supported measures. The indicators were as follows:

a. **Primary energy –** This is the sum of non-renewable energy sources that are drawn directly from the earth such as natural gas, oil, coal, or mineral fuels (for example, uranium). It included fuels combusted (to create and transmit) and used as fuel energy and is expressed in megajoules (MJ).

b. **Global warming potential (GWP) –** TRACI uses global warming potential for the calculation of the potency of greenhouse gases relative to CO_2. GWP can be considered one of the most accepted life-cycle impact assessment categories given the methodology and science behind its calculation.

c. **Acidification –** This comprises processes that increase the acidity (hydrogen ion concentration, [H+]) of water and soil systems (as per TRACI). Acidification is a more regional rather than global impact, affecting freshwater and forests as well as human health.

d. **Human health (HH) respiratory effects –** The TRACI midpoint is based on exposure to elevated particulate matter (PM)—particles found in the air, including dust, dirt, soot, smoke, and liquid droplets) less than 2.5 micrometres in diameter (PM2.5) that are referred to as "fine" particles and are believed to pose the greatest health risks. Particles less than 10 micrometres in diameter (PM10) pose a health concern, because they can be inhaled and accumulated in the respiratory system.

e. **Eutrophication –** This is the fertilization of surface waters by nutrients that were previously scarce (as per TRACI). This measure encompasses the release of mineral salts and their nutrient enrichment effects on waters. The result is expressed on an equivalent mass of nitrogen (N) basis.

[2] The 20-year assessment period was chosen to minimize the home's maintenance and replacement effects for materials and systems, as a number of the employed technologies either have uncertain life spans or may have deteriorating performance over time. Such a period, while arbitrary, is realistic from a decision-making perspective; that is, the advantages of a net-zero home should become readily evident within a 20-year period, if not sooner.

f. **Ozone depletion –** This is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances.

g. **Smog –** Smog is caused by air emissions from industry and transportation that, under certain climatic conditions, can be trapped at ground level. In the presence of sunlight, the emissions produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). The "smog" indicator is expressed on a mass of equivalent ethylene basis.

h. **Solid waste –** This indicator summarizes life-cycle impact of solid waste flows and is expressed in kg. It does not include occupant-related household waste.

i. **Water use –** This indicator summarizes life-cycle impact of water usage flows associated with the production of materials and energy and is expressed in m^3. It does not include occupant-related household water consumption.

This study was based on design information received for each dwelling, which included construction drawings, technical submission materials and a HOT2000 operating energy simulation file. All were used to calculate the materials used for each dwelling as well as those that would be used for the building code and R-2000 baseline cases. The conventional and advanced versions of the EQuilibrium projects were modelled in HOT2000 (v10.5) to determine annual operating energy use. The resulting material quantities and energy use were then entered into the Athena Institute's *Impact Estimator for Buildings* (v4.1) software and proprietary LCA software *SimaPro* (v7.18) to provide a complete life-cycle analysis of each dwelling scenario.

RESULTS

The six dwelling units that were assessed varied in terms of housing type, size (a significant factor as it directly relates to the conditioned space volume) and location. All six are located in one of three provinces—Alberta, Ontario or Quebec. Each dwelling location faces a unique number of heating degree-days (HDD), varying between 3,650 and 5,700. The reported air changes per hour for the dwellings indicated that the dwellings were very airtight, thus making mechanical ventilation a necessity. Table 1 summarizes the physical and operating characteristics of each of the projects (additional information on each of the selected projects can be found at www.cmhc.ca).

Predicted annual on-site energy use for the EQuilibrium projects was calculated to be between 41 and 99 kWh/m^2 across the six dwellings. The annual total predicted on-site renewable energy production was estimated to vary between 29 and 82 kWh/m^2 across the six dwellings, with two dwellings (Inspiration and Riverdale) producing more energy than they consumed (annually).

The results of the analysis indicated that the EQuilibrium houses are considerably more materially and technologically intensive relative to their conventional or advanced housing counterparts. However, the energy demand of the EQuilibrium dwellings was estimated to be between three to five times lower. The embodied effects of the additional materials and technologies employed in the EQuilibrium projects over a 20-year period accounted between 84% to 100% of the dwelling's overall impact. The environmental impact of the renewable energy and energy recovery systems used in the EQuilibrium dwellings were estimated to be significant and accounted for up to 30% of the total embodied effect of the dwellings over the first 20 years of operation.

Relative to the OBC and R-2000 benchmarks analyzed, over the 20-year, cradle-to-gate study period, the analysis indicated that the EQuilibrium baseline designs achieved the following:

- a reduction in primary energy consumption and global warming, acidification and human health respiratory effects;
- an increase in ozone depletion, water use and smog (except for the Riverdale project);
- a reduction in solid waste for Riverdale, Avalon and Inspiration, and an increase for Abondance and EcoTerra and;
- generally about the same performance in terms of eutrophication.

Table 1 EQuilibrium project design and construction characteristics

	Riverdale	Avalon	Inspiration	NOW	EcoTerra	Abondance
Site characteristics						
Location	Edmonton, Alberta	Red Deer, Alberta	Manotick, Ontario	Toronto, Ontario	Eastman, Quebec	Montreal, Quebec
Heating degree-days below 18°C	5,400	5,700	4,600	3,650	4,800	4,250
Dwelling Description						
Dwelling type	Semi-detached	Single-detached	Single-detached	Existing single-detached (renovation)	Single-detached	Multi-unit residential building (MURB)
Per unit conditioned floor space (m^2)	234	240	310	139	234	103
Foundation type	Full basement	Slab on grade	Full basement	Existing full basement	Full basement	Full basement
Wall system	Double 2x4 stud wall	Structural insulated panels (SIPS)	Double 2x4 stud wall	Existing 2x4 stud wall, furred out Larson truss retrofit	2x6 stud wall prefabricated system	2x6 stud wall
Roof	Gable trusses	Gable, cathedral trusses	Gable, cathedral trusses	Existing gable stick framed	Gable trusses, cathedral open web joists	Flat open web joists
Active systems						
Photovoltaic (kWp, per unit)	5.6	8.3	6.2	2.0	3.0	4.7
Solar thermal (m^2, per unit)	19.2	15.2	23.8	6.0	n/a	6.0
Space heating/domestic hot water	Solar collectors, drainwater heat recovery and electric resistance backup. Hydronic fan-coil forced-air distribution.	Solar collectors with electric boiler backup. Hydronic radiant floor distribution.	Solar collectors, drainwater heat recovery with 98% AFUE gas boiler backup. Hydronic fan-coil forced-air distribution.	Solar collectors, drainwater heat recovery and on-demand gas boiler backup. Hydronic fan-coil forced-air distribution.	Ground source heat pump, heat recovery from behind PV array and grid electricity backup. Forced air distribution.	Solar collectors, ground source heat pump, drainwater heat recovery and electric tank backup. Forced air distribution.
Ventilation	Integrated with ductwork, 48 L/s HRV	Dedicated ductwork, 60L/s HRV	Integrated with ductwork, 65 L/s HRV, air collector heaters	Integrated with ductwork, 55 L/s HRV	Integrated with ductwork, 50 L/s HRV	Integrated with ductwork, 25 L/s HRV
Thermal characteristics (RSI)						
Flat ceiling	17.6	15.3	11.0	8.8	8.8	12.3
Sloped ceiling	n/a	15.3	11.0	5.6	6.3	n/a
Above-grade walls	10.0	12.9	7.8	5.8	6.6	7.9
Below-grade walls	9.5	5.4	7.0	4.6	3.6	6.3
Basement floor slab	4.2	10.6	2.6	4.4	1.3	2.6
Windows	1.2-1.8	1.0	1.0	1.0	0.7	0.8
Air changes per hour @50Pa (ACH)	0.5	1.38	0.65	1.5	1	0.4
Estimated annual energy profile (kWh/m^2)						
Space heating	15.0	29.3	23.2	23.1	10.0	6.6
Space cooling	0.0	0.0	0.0	0.0	0.0	5.4
Domestic hot water	9.4	11.6	11.3	35.6	11.5	26.1
Ventilation	2.0	4.5	1.8	1.5	2.7	48.8
Appliances and lighting	16.4	14.5	13.3	36.8	16.6	12.5
On-site generation	44.3	56.1	51.6	39.4	29.0	82.3
Net energy consumption	-1.5	3.8	-2.0	57.6	11.8	17.1

	Riverdale	Avalon	Inspiration	NOW	EcoTerra	Abondance
Estimated annual operating fuel use						
Electricity (kWh)	-351	917	-3,498	2,260	2,775	1,317
Natural gas (m^3)	0	0	268	541	0	0
EQ baseline 20-year life cycle impacts						
Primary energy (MJ)	859,393	1,154,724	986,480	1,107,503	933,323	693,866
% embodied primary energy	*100.0%*	*83.6%*	*100.0%*	*29.3%*	*98.8%*	*99.0%*
Global warming (kg CO_2 eq.)	47,792	77,462	64,723	57,558	65,600	46,745
% embodied global warming	*100.0%*	*79.5%*	*100.0%*	*34.4%*	*99.6%*	*99.7%*
Acidification (moles of H+ eq.)	28,456	35,506	36,327	23,646	37,766	21,865
% embodied acidification	*100.0%*	*84.9%*	*100.0%*	*35.0%*	*99.9%*	*99.9%*
HH respiratory effects (kg PM2.5 eq.)	254.8	308.9	341.7	130.9	340.6	191.2
% embodied HH respiratory effects	*100.0%*	*89.2%*	*100.0%*	*41.7%*	*99.9%*	*99.9%*
Eutrophication (kg N eq.)	19.02	17.12	24.1	7.29	19.57	16.17
% embodied eutrophication	*100.0%*	*99.1%*	*100.0%*	*83.9%*	*99.9%*	*99.9%*
Ozone depletion (kg CFC-11 eq.)	1.53E-03	6.28E-05	1.96E-03	1.04E-03	7.14E-02	7.27E-02
% embodied ozone depletion	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Photochemical smog (kg NOx eq.)	243.7	380.8	314.5	92	308.3	158.9
% embodied photochemical smog	*100.0%*	*99.2%*	*100.0%*	*87.1%*	*99.9%*	*99.9%*
Solid waste (kg)	18,499	21,768	25,082	3,294	24,291	14,197
% embodied solid waste	*100.0%*	*90.9%*	*100.0%*	*58.6%*	*100.0%*	*100.0%*
Water use (m^3)	269.7	130.2	482.2	101	274.2	458.1
% embodied water use	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

The latter part of table 1 reports the 20-year life-cycle indicator results for the six EQ baseline dwellings. As the dwellings are estimated to attain or approach a net-zero operating energy result, the materials embodied in each dwelling become more significant. The table also shows the percentage of each indicator that is the result of material use. For example, the material-related primary energy use varies between 84 per cent and 100 per cent across the newly constructed dwellings—the percentage is considerably lower for the NOW House renovation project, because the original materials embodied in the pre-retrofit structure and envelope were treated as a sunk cost and were thus ignored in the assessment. As is evident, almost all of the environmental indicator results are largely a function of the materials embodied in the dwellings.

Figures 1 and 2 summarize total primary energy and global warming potential results for each of the life-cycle stages of the EQ baseline dwellings on a normalized per m^2 per HDD basis for the 20-year life-cycle period. The manufacturing of the materials required to construct each dwelling's structure and envelope and to maintain them over the first 20 years of their service lives dominates consumption for each dwelling except the NOW House on account of its higher operating energy consumption. The building service systems portion of the figure includes the embodied effects of heating, cooling and ventilation equipment, plumbing and electrical, and renewable energy systems. These systems are responsible for 11% to 32% of primary energy and 10% to 30% of the overall GWP impact. Both the Riverdale and Inspiration project homes, being estimated net producers of renewable electricity, actually offset some of the greenhouse gas emissions from their respective electricity grids, which further diminishes their overall GWP effect. The EcoTerra and Abondance homes purchase electricity from the Quebec's hydro-dominated grid and therefore are GWP-neutral.

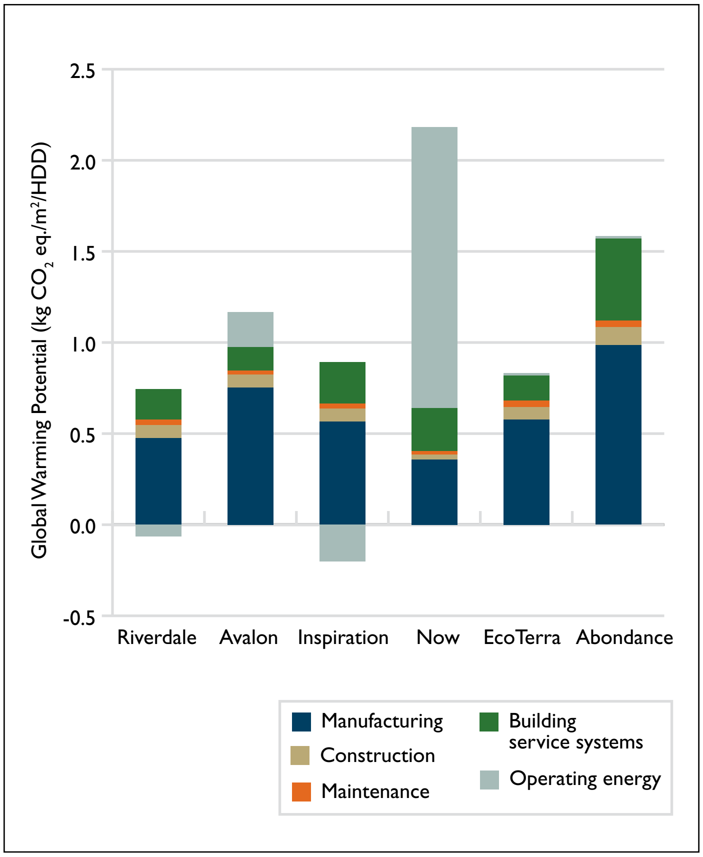

Figure 1 EQ baseline primary energy results, by life-cycle stage (MJ/m²/HDD) – 20-year life cycle

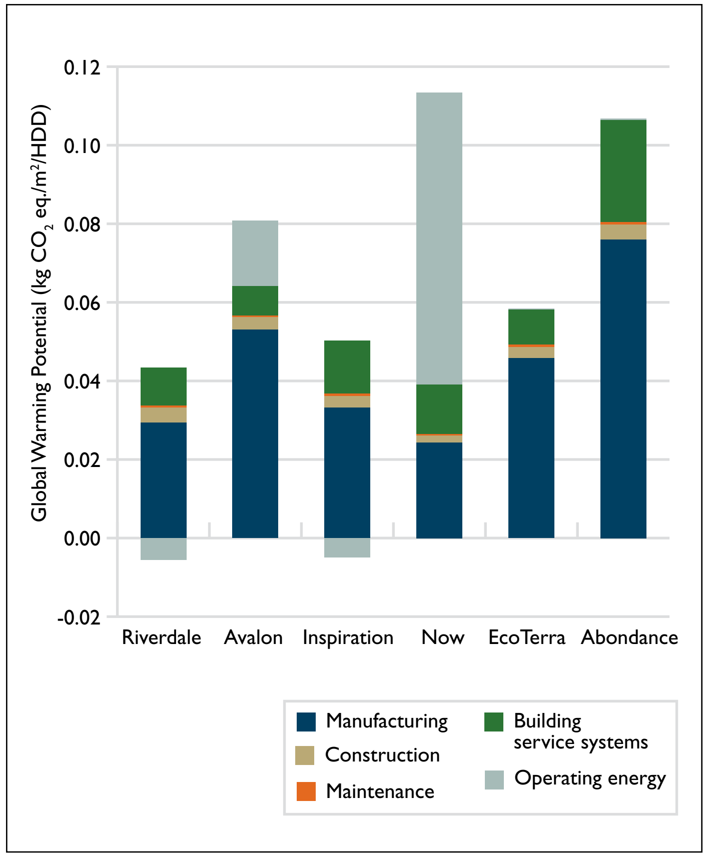

Figure 2 EQ baseline global warming potential results, by life-cycle stage (kg CO_2 eq./m²/HDD) – 20-year life cycle

Figure 3 provides the 20-life-cycle primary energy use associated with the EQuilibrium baselines along with their OBC and R-2000 equivalents. Although the EQuilibrium baselines may be more energy-intensive to build, Figure 3 shows that, over the longer term, the lower operating energy associated with net-zero, or near net-zero, annual energy consumption results in overall reduced energy use. Figure 4 illustrates how, for one project, the more materially intensive EQuilibrium design can have greater environmental impacts—in this case the contribution to smog potential during the manufacturing—in comparison to its OBC and R-2000 baselines.

CONCLUSIONS

This study focused on the life-cycle energy and environmental impacts of targeting highly energy-efficient, net-zero energy design objectives based on the designs of six EQuilibrium housing projects. The results indicated that the EQuilibrium designs were considerably more materially, technologically and hence energy-intensive relative to their conventional 2006 OBC or R-2000 design baselines. However, the operating energy demand of the EQuilibrium designs was found to be between three to five times lower than their comparable conventional and R-2000 versions. The results also demonstrate that the energy embodied in the projects targeting net-zero energy consumption makes up a much larger proportion of the overall life-cycle energy. For the projects studied, the embodied effects of the materials and technologies employed accounted for 84% to 100% of the dwelling's overall impact during the 20-year life-cycle period. The environmental impact of the renewable energy and energy recovery systems used in the EQuilibrium designs were also found to be significant and were estimated to account for up to 30% of total the embodied effect of the dwellings over the first 20 years of their operation.

Relative to the OBC and R-2000 benchmarks analyzed, over the 20-year, cradle-to-gate study period, the EQuilibrium baseline designs showed a reduction in primary energy consumption, global warming, acidification, and human

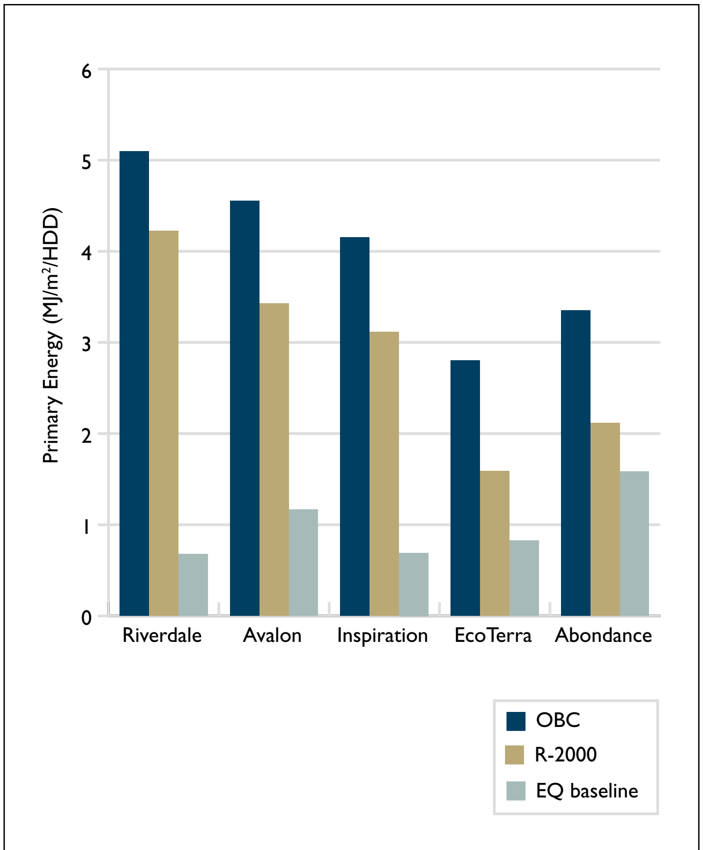

Figure 3 OBC, R-2000 and EQ baseline primary energy results (MJ/m²/HDD) - 20-year life cycle

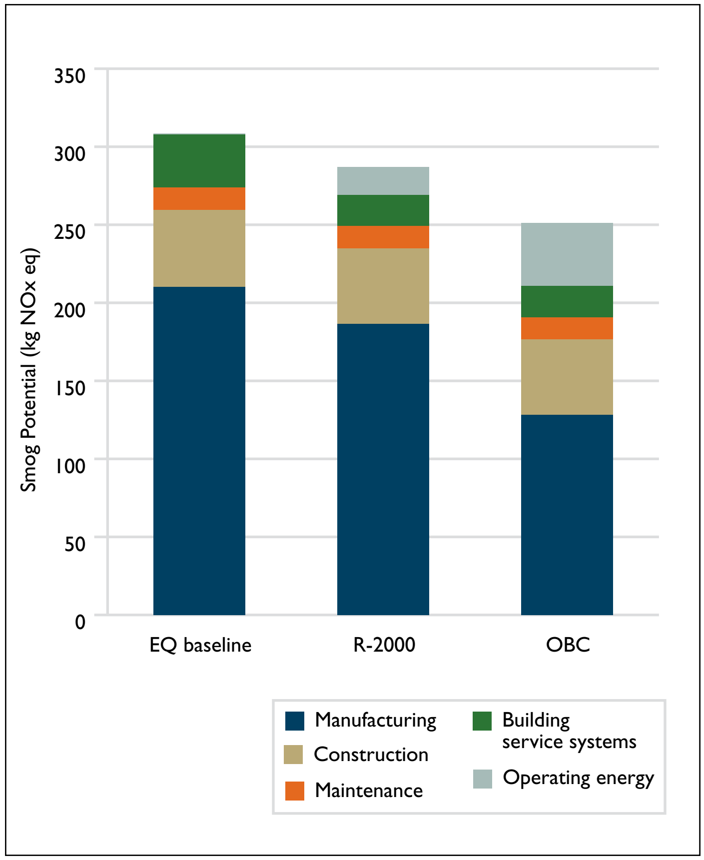

Figure 4 Smog potential, by life-cycle stage – EcoTerra – 20-year life cycle

health respiratory effects; an increase in ozone depletion, water use and smog (except for one project); a reduction in solid waste for 50% of the projects; and generally about the same performance in terms of eutrophication.

Through the study, it was possible to see some of the impacts associated with design decisions based on the different approaches taken to the design of each of the houses (that is, what systems and materials were used to achieve targeted performance) and the estimated life-cycle impacts on energy and the analyzed environmental indicators. The results show that designers can significantly reduce the environmental burden of housing by selecting materials of lower impact that perform the same function. Designers should also be aware of the local electricity generation mix a dwelling will draw from. For example, given Alberta's reliance on coal-based generation, electrically powered systems are generally responsible for much higher environmental impacts than natural gas fuelled systems. The opposite is generally true in Quebec, where electricity generation is dominated by lower-impact hydroelectric dams.

IMPLICATIONS FOR THE HOUSING INDUSTRY

These findings illustrate the benefits and trade-offs associated with the pursuit of net-zero energy design, namely, low operating energy consumption versus increased material usage and higher related embodied energy. The study shows that residential energy efficiency measures and renewable energy generation systems are effective means to lower overall life-cycle energy use and many environmental impacts—though not all. As housing design becomes ever more energy-efficient in the future, the embodied contribution will become a greater share of total life-cycle effects. It will become necessary to better understand the implications of material choices to ensure operating energy objectives do not come at the expense of increased embodied energy use and environmental impacts.

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Housing Research at CMHC

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Alternative text and data for figures

Figure 1 EQ baseline primary energy results, by life-cycle stage (MJ/m^2/HDD) – 20-year life cycle

	Manufacturing	Construction	Maintenance	Building service systems	Operating energy
Riverdale	0.476	0.071	0.03	0.168	-0.064
Avalon	0.754	0.071	0.02	0.131	0.191
Inspiration	0.566	0.071	0.03	0.227	-0.2
Now	0.358	0.028	0.019	0.236	1.543
EcoTerra	0.577	0.067	0.036	0.137	0.013
Abondance	0.985	0.1	0.035	0.449	0.016

Figure 2 EQ baseline global warming potential results, by life-cycle stage (kg CO_2eq./m^2/HDD) – 20-year life cycle

	Manufacturing	Construction	Maintenance	Building service systems	Operating energy
Riverdale	0.029	0.004	0.0006	0.01	-0.0055
Avalon	0.053	0.003	0.0004	0.008	0.0165
Inspiration	0.033	0.003	0.0006	0.013	-0.0048
Now	0.024	0.002	0.0004	0.013	0.0744
EcoTerra	0.045	0.003	0.0007	0.009	0.0003
Abondance	0.076	0.004	0.0007	0.026	0.0004

Figure 3 OBC, R-2000 and EQ baseline primary energy results (MJ/m^2/HDD) – 20-year life cycle

	OBC	R-2000	EQ Baseline
Riverdale	5.1	4.2	0.7
Avalon	4.6	3.4	1.2
Inspiration	4.2	3.1	0.7
EcoTerra	2.8	1.6	0.8
Abondance	3.3	2.1	1.6

Figure 4 Smog potential, by life-cycle stage – EcoTerra – 20-year life cycle

	Manufacturing	Construction	Maintenance	Building service systems	Operating energy
EQ Baseline	210.1	49.5	14.2	34	0.4
R-2000	186.6	48.3	14.2	20	18
OBC	128.3	48.3	14.1	20	40.4