A Full Life-Cycle Environmental and Cost Evaluation of Commercial Wall Envelope Systems

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ABSTRACT

This paper compares and contrasts nine typical commercial wall systems, taking into consideration their respective material environmental life-cycle burdens, operating energy effects, direct construction and operating energy costs, and indirect costs, or what are known as social or externality costs.

Using commercially available environmental life-cycle assessment, operating energy, and direct construction cost databases and software tools, as well as public sources for fuel prices and externality costs of material and energy use-related emissions to air, water, and land, the full environmental life-cycle costs of each wall system was estimated over a 20-year time period as built in Toronto.

The paper describes life-cycle analysis and full-cost accounting, including environmental externality costs—the additional costs to society in terms of human health and environmental damage that are not incorporated into our present economic system. The integration of life-cycle assessment, life-cycle costing, and externality costs in one method solves the problem of having to intrinsically weigh direct costs against the array of environmental burdens as all results are expressed in monetary terms—a terminology that all decision makers understand and can appreciate.

This more robust decision-making framework offers us a method for moving away from what some would call our current subjective or prescriptive decision-making process, with its inherent pitfalls, to one that is more holistic, objective, and ultimately performance based.

INTRODUCTION

Historically, energy codes, technical utility, and first cost have driven the specification of wall envelope components and systems for buildings. Of late there has been a movement to incorporate environmentally "green" materials into buildings, but these efforts have often been subjective and single-criterion oriented (e.g., low-VOC paints or materials containing higher recycled content levels). Environmental life-cycle assessment (LCA) in combination with full-cost accounting offers a more holistic and performance-based decision-making framework for determining more environmentally efficient and cost-effective building solutions. This paper demonstrates the power of combining these two tools by comparing and contrasting nine wall types of varying material compositions and their effective thermal resistances to determine the optimal wall system from both an economic and environmental perspective. While the paper explores commercial wall systems, a number of these would also be applicable to the residential construction sector.

The paper first puts the baseline office building into context in terms of its size, basic components, and the default or typical wall envelope. The baseline building's embodied effects and operating energy are then simulated over a twenty-year period. In addition, the direct costs of constructing and operating the building and the indirect (social) costs of the building's emissions to air, water, and land are estimated over the same 20-year period. These initial results provide an order of magnitude indication of the environmental burdens and

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economic costs associated with a small office building in Toronto. With this baseline established, we then replace the default wall envelope with each of the remaining eight wall types and compare the net incremental change in the building's operating energy and environmental and economic metrics over the same 20-year timeframe relative to the default wall envelope. Hence, in an iterative fashion, the study provides a solution as to which combination of building materials and thermal resistance are the most cost-effective for the opaque wall envelope from both an economic and environmental perspective.

BACKGROUND AND METHODOLOGY

In the process of completing this project, we drew on a number of simulation tools, concepts, and secondary data. This section provides a brief overview of the tools, relevant concepts, and secondary data sources.

Construction Costs and Embodied Environmental Effects

Direct construction costs for the baseline building and the alternative wall envelope systems were developed using *RS Means Building Construction Cost Data* (2003 SI edition). The methods used to calculate construction costs include a detailed breakdown by wall materials and assigning costs to each wall component or system as described in the Means publication. The costs include all labor, materials, overhead, and profit required to construct the baseline building and various alternative wall systems. The costs were adjusted, as indicated in Means, to reflect the building location (Toronto Ontario, Canada).

We used a life-cycle assessment tool to determine the embodied environmental effects of the baseline building and various wall envelope systems. A full life-cycle assessment is a formal process of examining the environmental effects of a material or product through its entire life cycle, from raw resource or material acquisition through manufacture and use to waste disposal. Instead of a single-attribute analysis of a material's environmental impact, such as its recycled content, LCA takes a holistic approach to the possible impacts of a material throughout its life cycle.

A life-cycle inventory (LCI) is fundamental to an LCA. As the name implies, the LCI involves collecting and documenting data on the relevant environmental flows or burdens associated with the various life-cycle stages, including transportation within and between stages and the upstream effects of energy use (i.e., the energy and emissions associated with producing and moving energy). While LCI/LCA has been around in various forms since the early 1960s, it was only in the mid-to-late 1990s that the protocol for completing such studies was standardized by the International Organization for Standardization (ISO 14040-42). Currently, the Athena Institute's *Environmental Impact Estimator* (EIE) software (v 3.0) encompasses LCI profiles for steel, wood, and concrete structural products and assemblies, as well as a full range of envelope materials (e.g., cladding, insulation, glazing, roofing, etc.). It also covers a building's life-cycle stages from the "cradle" (natural resource extraction or recycling facility) to its end of life (grave). Specifically, the model encompasses the following building life-cycle stages:

- *Product manufacturing*: includes resource extraction (from nature or the technosphere), resource transportation, and manufacturing of materials, products, or building components
- *On-site construction*: includes product/component transportation from the point of manufacture to the building site and on-site construction activities
- *Maintenance and replacement*: includes life-cycle maintenance and replacement activities associated with the structure and envelope components based on building type, location, and a user-defined life for the building
- *Building "end-of-life":* simulates demolition energy and final disposition of the materials incorporated in a building at the end of the building's life

The software also includes a calculator to convert operating energy to primary energy and generate emissions to allow users to compare embodied and operating energy environmental effects over the building's life. The operating energy calculator requires a separate estimate of operating energy as an input to the model. EQUEST annual fuel consumption simulation results by fuel type for the base building and each of the wall design scenarios were entered into the EIE software (see next section for a discussion of EQUEST). The software then estimated the primary energy and related emissions to air, water, and land associated with the type and quantity of fuels used for each wall envelope scenario.

In terms of results, the software provides a detailed environmental life-cycle inventory of the embodied effects associated with the building as well as a set of six summary measures. These summary measures include primary (embodied) energy and raw material use, greenhouse gas potential (both fuel and process related), measures of air and water pollution, and solid waste emissions. For this paper, results reporting of material effects has been purposely limited to embodied energy and global-warming potential as indicators of environmental burden.

Embodied primary energy is reported in giga-joules (Gj) and includes all nonrenewable energy, direct and indirect, used to transform or transport raw materials into products and buildings. Also included in this measure is the inherent energy contained in raw or feedstock materials that are also used as common energy sources (for example, natural gas used as a raw material in the production of various plastic [polymer] resins). In addition, the model captures the indirect energy use associated with processing, transporting, converting, and delivering fuel and energy. Global warming potential (GWP) is a reference measure for greenhouse gas emissions and is reported on a mass basis. Carbon dioxide is the common reference standard for global warming or greenhouse gas effects.

All other greenhouse gases are referred to as having a "CO_2 equivalence effect," which is simply a multiple of the greenhouse potential (heat-trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time. As yet, no consensus has been reached among policymakers about the most appropriate time horizon for greenhouse gas calculations. The 100-year time horizon figures of the International Panel on Climate Change have been used here as a basis for the equivalence index:

$$CO_2 \text{ Equivalent t} = CO_2 \text{ t} + (CH_4 \text{ t} \times 23) + (N_2O \text{ t} \times 296)$$
$$[\text{t} = \text{tons}]$$

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modeling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). Because Athena™ uses data developed by a detailed life-cycle modeling approach, all relevant process emissions of greenhouse gases are included in the resultant global-warming potential index.

The software and its embedded databases are North American in scope, representing average or typical manufacturing technologies and appropriate modes and distances for transportation. The model simulates 12 geographic regions represented by Vancouver, Calgary, Winnipeg, Toronto, Ottawa, Montreal, Quebec City, Halifax, Minneapolis, Atlanta, Pittsburgh, and a U.S. average. This study drew on the Toronto regional databases. The results also exclude any maintenance or "end-of-life" effects due to limiting the assessment to the building's first 20 years.

Operating Energy Use, Costs, and Environmental Effects

An estimate of operating energy use was developed using the EQUEST version 3 software (available at <www.doe2.com>). EQUEST is a complete, fully interactive, DOE-2.2 simulation environment for use in the current generation of Windows operating systems. EQUEST allows detailed analysis of building materials and systems and includes effects of HVAC systems, envelope systems, geometry, size, and location. Results from EQUEST include a wide array of energy use items broken down by specific equipment.

For this paper, the common properties of each simulated building were as follows:

- Located in Toronto, Ontario, Canada
- Two stories
- Total height of 7.2 m
- Suspended ceilings
- Total perimeter = 91 m
- Rectangular shape in plan, long side facing north
- Total usable floor space of 2,300 m^2
- Cooling equipment: DX coils (electric)
- Heating equipment: natural gas furnace, 85% efficient
- Perimeter / core zoning pattern
- Insulated slab-on-grade (50 mm [2 in.] extruded polystyrene)
- Steel frame
- Insulated roof (50 mm [2 in.] extruded polystyrene)
- 40% of each wall is strip windows (double glazed, low-E, argon filled)

Each of the simulations had identical building properties, with the exception of the exterior opaque wall elements (see "Wall Types Considered" below). This allowed an analysis of the environmental and economic differences between the various wall alternatives. Energy loads other than those that the envelope may influence were ignored (e.g., plug-loads, hot water heating, and lighting).

The two operating energy fuels of concern are natural gas and electricity. Natural gas prices have been on the increase in recent years and are currently quoted at \$0.35/m^3 (including transportation). In 2003, nonresidential electricity rates were \$0.083/kWh in Toronto. These energy prices, combined with the fuel quantities from EQUEST, provide the base operating energy cost.

The absolute environmental effects of operating energy use (i.e., releases to air, water, and land) were estimated using the EIE software as described previously.

Indirect (Externality) Costs

While supply and demand influence direct prices, which is another way of saying that direct price is a measure of immediate scarcity of a good or service, indirect costs are those that are borne by society, if not now then at some future date, but are not explicitly considered in the prevailing price of goods or services. Typically, these external costs to society include pollutants in the form of emissions to air, water, and land and the general degradation of the ambient environment. By not accounting for these myriad of environmental effects, the prevailing price system is skewing our understanding of the environmental costs and benefits associated with the products and services we choose to use. Some argue that we are liquidating our ecological capital with no way of accounting for this depreciation on our books. Still others argue that these costs that are currently treated as "external" to our economic decision making are often larger and more important than the "internal" factors that actually drive our economic decision making. For example, in 1997 a group of ecologists and environmentalists estimated the monetary value of the free services nature provides to be \$50 trillion annually—that is roughly twice the GNP of the world economy in 1997 (David Suzuki Foundation 2002). Applying externality costing can begin to provide a fuller understanding of the true costs of our decisions on society and our planet.

In time we may see more environmental factors embodied in the price system (e.g., carbon or energy taxes) and therefore in the cost of goods and services; however, the use of market forces to achieve environmental objectives is not being readily adopted. The remainder of this section briefly describes methods from the literature for estimating "externality costs," provides a range of indirect prices for some air emissions, and applies these price ranges to the pollutants emanating from building and operating an office building, with various wall envelopes, over its first 20 years of operation.

There are two principal families of approaches to estimating externality cost factors per unit of pollutant release: cost-of-control methods and damage methods (Norris 2002). Both methods have been applied to LCA applications in the past (and present). Wang and Santini (1995) demonstrated how damage estimation versus control cost estimation methods could lead to results that differ by a factor of 100 or greater in some instances. The earliest application appears to be use of a (mostly) cost-of-control method by Tellus in the early 1990s. This set of applications actually generated a firestorm of criticism for the following reasons:

- For nearly all pollutants, there is nearly an infinite set of possible control options, and the selection among them can lead to orders of magnitude difference in resulting cost factors.
- Technology change continues to change the costs of some control options, so that for long-lived products (such as buildings) an additional uncertainty is introduced.

Damage estimation has been applied in an increasing number of cases during the past five to ten years both within and tangential to the field of LCA. Indeed, a case can be made that the life-cycle impact assessment (LCIA) field is moving steadily away from its historical midpoint indicator approach toward damage estimation approaches. The damage estimation approach is closely linked with the body of risk assessment methods and involves a sequence of modeling steps generally categorized as follows:

Fate/Transport Modeling → Exposure Assessment →Damage Assessment → Valuation

We have borrowed on this growing body of damage estimation literature to arrive at pollutant cost factors for use in this paper. In addition to the source of data, a number of issues persist with the use of the damage function approach:

- More recently, regionalized impact factors have been developed for use in LCIA, which take into account the influence of source location on expected impacts. These advancements have shown that the location of a release can have a strong influence upon its expected impact.
- Another issue is whether the damage factor represents the average damage per kg released or the incremental damage from an additional kg of emission. This is commonly referred to as the marginal versus average damage factor issue, but little light has been shed on it to date.
- Human health air pollutant endpoints are by far the most extensively studied to date. Also, preliminary studies of other types of impact (such as damage to ecosystems, crops, and structures/monuments and the depletion of resources) have tended to indicate that human health impacts constitute a large portion of the total damage value. But this may be a self-fulfilling prophecy if human health is unduly valued over, say, an ecosystem. Or in the words of some environmentalists, humans are not in short supply on this planet, but we only have a fixed (or decreasing) amount of ecosystem.

Obviously, externality costing is not without its problems, but to completely discount these costs when making decisions about long-lived durable products, such as buildings, is, to say the least, short-sighted. Given the prevailing uncertainty surrounding externality costing, we have calculated high and low externality values that are somewhat narrower than the extremes evident in the published literature. The intent is to reflect the strong variability among estimates without adopting the extreme outliers as our scenario values. We report low-end values that are roughly midway between centrally tending values and the low-end extremes, and we adopt high-end values that are roughly midway between centrally tending values and the high-end extremes. Finally, we calculate and use in this paper a simple midpoint between the calculated high- and low-end values for each pollutant in order to provide a central value. Further, for all other emissions for which externality costs are not known, we have arbitrarily valued them at the known cost of the least polluting air emission within the scenario, which in all cases is carbon dioxide. The use of this lowest valued emission to represent the externality costs of all other emissions, regardless of type or quantity, has a tendency to underestimate the true externality cost of these emissions for which the externality costs are unknown. Or, in other words, we are putting more emphasis on the externality costs of the emissions we know best (fuel combustion related) and

Table 1. Damage Values for Air Pollutants (C$2003/kg)

NO_x			VOCs			CO			PM10			SO_2			CO_2		
High	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid
31	3	18	18	2	10	5	2	3	48	3	26	20	3	12	0.073	0.021	0.048

Sources: Wang and Santini (1995)—Values from their Table 1, converted from 1989 dollars. Leach et al. (1997), which adapted data from a literature review by Hormandinger (1995). Values adopted from Leach et al.'s Figure 4 and converted from 1996 British pounds.

are knowingly being conservative about the externality costs associated with all other emissions (e.g., manufacturing process emissions).

Last, there is the issue of whether the externality costs of pollutant emissions over time should be discounted, to arrive at a present dollar value. Discounting of long-term environmental damages such as resource depletion and climate change has been criticized by many authors, from a variety of angles. The main thrust is the fact that discounting at rates of 2% to 3% or more leads to nearly zero-valuing of impacts occurring at times beyond 100 years hence. Thus, discounting at rates above 2% to 3% would allow near-term consumption at the expense of potentially massive damages to future generations. This result may perhaps be surprising; it results from the counterintuitive power of exponential growth, or compounding interest, here being invoked due to the assumption of 2% to 4% annual economic growth over very long periods of time. At a 3% annual growth rate, $1 will become $19 after 100 years and $7099 after 300 years. By this logic, damages worth $7099 incurred 300 years from now are not worth investing more than $1 to prevent at present. It is our assertion that emissions over time should not be discounted (adjusted for inflation), and to this end current cost(s) are maintained throughout the study's 20-year time period.

In summary, all externality costs reported in this paper draw on nondiscounted midpoint estimates and are valued in 2003 Canadian dollars.

WALL TYPES CONSIDERED

Nine common wall types were selected for comparison. These wall types were chosen to represent varying thermal conductivities for three different base materials (wood, steel, and concrete). Each wall type is constructible and represents plausible or common constructions in North America for small office complexes. Note that it was not the intent of this paper to create equal thermal conductance properties across the varying material types but, rather, to select relatively common and constructible wall types with different thermal properties.

For each wall type, information on direct and indirect costs, operating energy costs, and material and operating life-cycle burdens and effects were calculated, as described above. The specific construction and attributes of the various wall types are listed in Table 2.

Wood-Based Wall Systems

Three wood-based wall systems were selected, based on varying thermal conductivities. The wall types were denoted Wood 1, Wood 2, and Wood 3 and represent brick-clad systems with relatively low (RSI 2.2 m^2K/W), medium (RSI 3.4 m^2K/W), and high (RSI 5.5 m^2K/W) thermal resistance.[1] Wall types Wood 1 and Wood 2 can be described as a 2×4 and 2×6 insulated assemblies respectively. Wall type Wood 3 can be described as a double offset insulated stud assembly. The construction of the specific wood wall types is listed (from the interior to exterior) in Table 2.

Steel-Based Wall Systems

Three steel-based wall systems were selected, based on varying thermal conductivities. The wall types were denoted Steel 1, Steel 2, and Steel 3 and represent brick-clad systems with relatively low (RSI 1.4 m^2K/W), medium (RSI 2.7 m^2K/W), and high (RSI 3.8 m^2K/W) thermal resistances. Wall type Steel 1 is a 92 mm stud wall with glass fiber insulation within the studs. Wall type Steel 2 is similar to Steel 1 except with 150 mm studs (and insulation), and 1 in. expanded polystyrene insulation sheathing was utilized. Wall type Steel 3 was similar to Steel 2, except that 75 mm of expanded polystyrene sheathing was utilized. The construction of the specific steel wall types is listed (from the interior to exterior) in Table 2.

Concrete/Masonry-Based Wall Systems

Three concrete masonry-based wall systems were selected, based on varying thermal conductivities. The wall types were denoted Conc1, Conc2, and Conc3 and represent brick-clad systems with relatively low (RSI 0.6 m^2K/W), medium (RSI 2.4 m^2K/W), and high (RSI 3.7 m^2K/W) thermal resistances. Wall type Conc1 is an uninsulated concrete block wall assembly. Wall type Conc2 is a concrete block wall with an insulated 2×4 wood wall to the interior. Wall type Conc3 was similar to Conc2, except that 75 mm expanded polystyrene was utilized on the exterior of the concrete block. The construction of the specific concrete/masonry wall types is listed (from the interior to exterior) in Table 2.

RESULTS AND DISCUSSION

This section describes the results for both the baseline building and the net incremental differences between the various wall envelopes relative to the baseline default wall.

Baseline Building Results

Table 3 summarizes the primary energy and greenhouse gas results for the baseline building inclusive of material effects (from resource extraction through to completion of the building on site) and operating energy effects (electricity use involved with space heating and cooling as well natural gas use for space heating) for the first 20 years of the building's life. The building's materials are responsible for about 20% of the building's primary energy and greenhouse gas effect. Alternatively, one could say that the material environmental effects are equivalent to about four years of operating energy.

Table 4 provides the direct and indirect costs associated with building and operating the small office building in Toronto for a period of 20 years. Direct construction cost is responsible for the bulk of the building's total cost. The direct cost of the energy to heat and cool the building accounts for

[1] Thermal resistance properties (RSI) were an output of the EQUEST software.

Table 2. Construction of Wall Systems

Wood-Based Wall Systems		
Wood 1	Wood 2	Wood 3
12 mm gypsum board	12 mm gypsum board	12 mm gypsum board
6 mil polyethylene	6 mil polyethylene	6 mil polyethylene
2×4 wood studs @406 mm o.c.	2×6 wood studs @406 mm o.c.	2×4 wood studs @406 mm o.c.
glass fiber batt within studs	glass fiber batt within studs	glass fiber batt within studs
12 mm plywood sheathing	12 mm plywood sheathing	2×4 wood studs @406 mm o.c. (staggered)
15# asphaltic building paper	#15 asphaltic building paper	glass fiber batt within studs
vented 20 mm airspace	vented 20 mm airspace	12 mm plywood sheathing
100 mm brick	100 mm brick	#15 asphaltic building paper
		vented 20 mm airspace
		100 mm brick
Steel-Based Wall Systems		
Steel 1	Steel 2	Steel 3
12 mm gypsum board	12 mm gypsum board	12 mm gypsum board
6 mil polyethylene	6 mil polyethylene	6 mil polyethylene
92 mm steel studs @406 mm o.c.	150 mm steel @406 mm o.c.	150 mm steel @406 mm o.c.
glass fiber batt within studs	glass fiber batt within studs	glass fiber batt within studs
12 mm gypsum board sheathing	25 mm EPS type III sheathing	75 mm EPS type III sheathing
#15 asphaltic building paper	#15 asphaltic building paper	#15 asphaltic building paper
vented 20 mm airspace	vented 20 mm airspace	vented 20 mm airspace
100 mm brick	100 mm brick	100 mm brick
Concrete/Masonry-Based Wall Systems		
Conc 1	Conc 2	Conc 3
12 mm gypsum board	12 mm gypsum board	12 mm gypsum board
6 mil polyethylene	6 mil polyethylene	6 mil polyethylene
12 mm air space with wood strapping at 600 mm o.c.	2×4 wood studs @406 mm o.c.	2×4 wood studs @406 mm o.c.
200 mm concrete block	glass fiber batt within studs	glass fiber batt within studs
#15 asphaltic building paper	200 mm concrete block	200 mm concrete block
vented 20 mm airspace	25 mm EPS type III sheathing	75 mm EPS type III sheathing
100 mm brick	#15 asphaltic building paper	#15 asphaltic building paper
	vented 20 mm airspace	vented 20 mm airspace
	100 mm brick	100 mm brick

Table 3. Baseline Building Material and 20-year Operating Energy Effects

	Primary Energy GJ	Global Warming Potential Equiv. CO_2 T
Materials effect	4501	230
20-yr operating effect	22325	812
Total material and operating effect	26826	1042

Table 4. Baseline Building Direct and Indirect Costs over 20 Years

	Baseline Building Cost in C2003$	% of Total
Direct construction cost	1,350,000	73
Direct operating energy fuel cost	184,000	10
Indirect material cost	115,000	6
Indirect operating energy fuel cost	203,000	11
Total direct and indirect effect	1,852,000	100
Note: Cost of construction estimated at $135/ft^2 ($1450/m^2); however, direct construction cost can range between $50 to $150 per square foot for this archetype.		

roughly 10% of all costs, and the indirect costs, those borne by society, amount to 17% of the total cost of the building. It is interesting to note that the materials effect relative to operating energy effect was 4:1 in terms of primary energy (see Table 3), but on an indirect cost basis the ratio has decreased to 2:1. This result indicates that there are more releases to air, water, and land associated with the materials in the building than with the fuel energy used to heat and cool the building.

Wall Type Comparison of Differences

This section of the paper discusses the implications of changing the material makeup and thermal resistance of the opaque wall envelope, relative to the default wall system, in terms of primary energy consumption, greenhouse gas emissions, and direct and indirect costs.

Figure 1 shows the relative primary energy embodied in each of the wall envelopes. Based on the premise that it would be most responsible to try and achieve the highest thermal resistance with little or no additional primary energy embodied in the envelope, as compared to the default system, the results displayed in the graph suggest that the wood envelope options provide the best solution. Two of the wood walls (W1 and W2) actually have a lower primary embodied energy than the default wall (S1) and the third wood wall attains the highest thermal resistance of all the walls considered with only a slightly higher embodied energy than the default wall. Substituting wood for steel and glass fiber for EPS insulation work in favor of the wood wall. All concrete wall envelope solu-

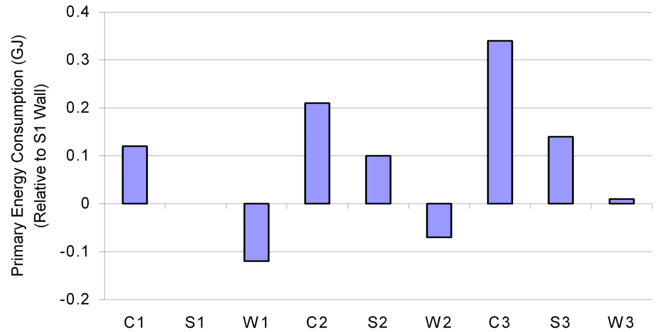

Figure 1 *Embodied material primary energy consumption.*

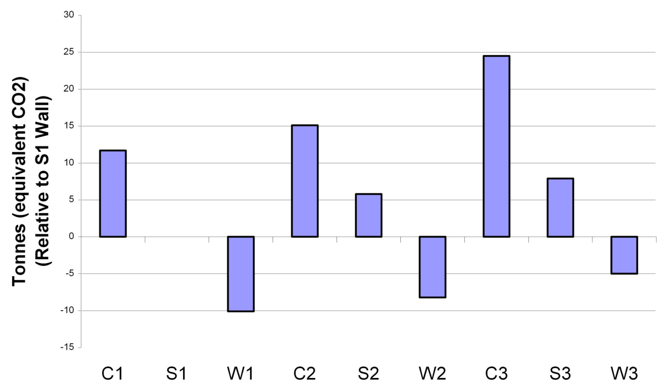

Figure 2 *Embodied material global warming potential.*

tions, regardless of thermal efficiency, embody more primary energy than the default wall system.

Figure 2 presents the global warming potential (GWP) associated with the materials making up each of the alternative wall envelopes, again, relative to the default wall (S1). The direct relationship between energy use and greenhouse gases is underscored as this figure closely mirrors that of the embodied primary energy graph. However, the GWP for the concrete envelope systems is somewhat higher than would be suggested by primary energy alone due to the process CO_2 emissions in the calcination of limestone during cement production and the wood envelope GWP is somewhat lower due to the fact that much of its manufacturing energy is derived from renewable biomass fuel that is considered to be GWP neutral.

Given the limited information on primary energy and GWP effects and assuming all things being equal, the results advise that we change the wall envelope to one of the wood envelope solutions.

Table 5 describes the relative direct construction cost premium and direct operating energy cost trade-off across the various wall options. Only the relative direct cost of constructing wall W1 is less than the default wall. However, all walls except C1 provide a direct operating energy cost savings over and above that of the S1 wall, due to their higher thermal resis-

Table 5. Direct Cost Comparison Across Wall Envelope Systems

Wall Envelope System	Direct Construction Cost in C2003$	Direct Operating Cost in C2003$ (for 20-year period)	Total Direct Cost in C2003$
C1	11274	14291	25564
S1	0	0	0
W1	-121	-3637	-3758
C2	15459	-4367	11092
S2	810	-4850	-4040
W2	1042	-5756	-4714
C3	20110	-6596	13514
S3	2437	-6266	-3828
W3	10809	-7303	3506

Table 6. Indirect Cost Comparison Across Wall Envelope Systems

Wall Envelope System	Indirect Construction Cost in C2003$	Indirect Operating Cost in C2003$ (for 20-year period)	Total Indirect Cost in C2003$
C1	3070	16327	19397
S1	0	0	0
W1	-1711	-4217	-5928
C2	4881	-5057	-176
S2	1853	-5621	-3768
W2	-688	-6677	-7365
C3	7065	-7614	-549
S3	2654	-7266	-4612
W3	532	-8477	-7945

tance. In fact, walls W1, S2, W2, and S3 more than offset their higher direct construction cost with corresponding operating energy cost savings. Based on these direct costs alone, one could come to the conclusion that wall systems W1, S2, W2, and S3 would all be good choices (within $1000 of each other) for the building's envelope. But the environmental burdens associated with these wall systems as depicted in the previous graphs indicate that the wood envelope solutions, including W3, clearly outperform the steel alternatives.

The indirect or externality costs associated with constructing and operating the building monetize these environmental burdens associated with each wall alternative relative to S1 (Table 6) and provide a different perspective and result. The relative indirect costs of constructing the alternative walls are generally higher than that of S1 as they incorporate more materials. The wood walls W1 and W2 are noted exceptions to this observation. As previously mentioned, the wood alternatives compare favorably from an indirect cost perspective due to their low embodied energy (read fewer emissions) and their use of renewable biomass fuel. In terms of indirect operating energy costs, all the walls having a higher thermal resistance than the default wall exhibit a cost savings that appears to be proportional to the wall's relative thermal resistance. This mirrors the finding noted for direct operating energy cost savings; however, it is interesting to note that the indirect costs of the emissions from fuel combustion are actually higher than the direct costs incurred to purchase the fuel energy; suggesting that the full real cost of energy is about twice the prevailing price. Moreover, these indirect operating energy cost savings generally offset the higher indirect cost of constructing the more thermally efficient wall envelopes—a quite different outcome than was revealed by summing the direct cost of construction with direct operating costs.

Table 7. Direct and Indirect Cost Comparison Across Wall Envelope Systems

Wall Envelope System	Total Direct Cost in C2003$	Total Indirect Cost in C2003$ (for 20-year period)	Total Full Cost in C2003$
C1	25564	19397	44961
S1	0	0	0
W1	-3758	-5928	-9685
C2	11092	-176	10916
S2	-4040	-3768	-7808
W2	-4714	-7365	-12079
C3	13514	-549	12965
S3	-3828	-4612	-8441
W3	3506	-7945	-4439

Table 7 combines the direct and indirect costs and presents the full cost for each of the wall envelopes relative to the S1 default wall. On a direct cost basis alone, four wall systems outperform the default wall and are within $1000 of each other, but with the addition of the indirect cost information, the full cost spread between the wall systems becomes more pronounced. The best wall envelope solution for the building is W2 followed by W1, S3, and S2.

SUMMARY

This paper has demonstrated that full cost accounting—integrating environmental life-cycle assessment, traditional cost accounting, and externality costing—can lead to better decisions and reduces the burden on the part of the decision maker to subjectively weigh direct costs against physical environmental burdens.

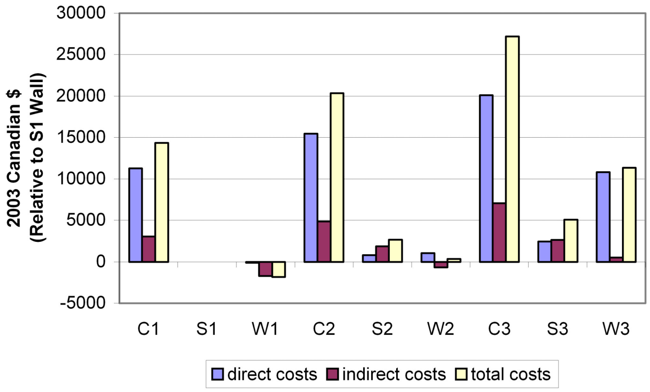

Figure 3 *Embodied material related direct and indirect costs.*

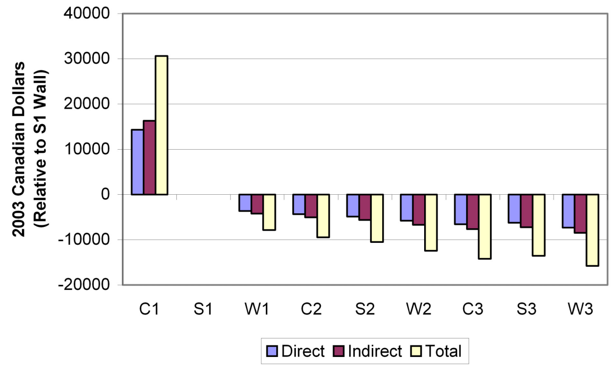

Figure 4 *Twenty-year operating energy related to direct and indirect costs.*

In the choice of wall envelope presented in this paper, direct cost comparisons of construction and operating energy narrowed the choice of nine potential wall systems down to four systems with fairly similar costs. However, it was the addition of indirect costs that led to uncovering the best system in terms of both out-of-pocket direct costs and minimizing environmental impact. These results are shown in Figures 3 and 4, which display both the direct and indirect costs associated with materials and operating costs for each wall (relative to the default wall), respectively. Figure 5 summarizes the total full cost of each wall envelope system on the basis of capital (material) and operating energy costs.

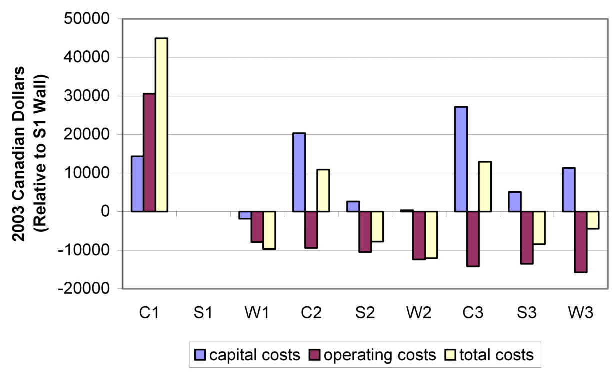

Figure 5 *Full embodied material and twenty-year operating energy costs.*

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