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The Path to Life Cycle Carbon Neutrality in High Rise Buildings

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Abstract

Across the world, building energy codes are becoming stricter, demanding higher levels of energy performance with each issuance. Some locations have taken initiatives to eliminate operational emissions altogether by requiring buildings to be carbon neutral. However, while the objectives of carbon neutrality are without doubt statement worthy, we believe that once operational performance has been tackled to a reasonable level of performance the sights should be trained on a different objective-life; cycle carbon. This paper defines what we mean by life cycle carbon neutrality and presents an approach toward reducing it.

Keywords: Life cycle, Embodied carbon, Operation carbon

1. Introduction

Long before the concerns over increasing CO2 levels and the resultant climate change predictions became daily headlines, there were initiatives to reduce energy demand of buildings through the application of building energy performance standards. In 1989 the American Society of Heating Refrigerating and Air-conditioning Engineers released standard ASHRAE 90.1 (ASHRAE, 1989) which brought about a reduction in energy use intensity of 14% compared with the previous standard – ASHRAE 90 which had remained largely unchanged since 1975. Subsequent iterations of this standard, which have been three-yearly since 2001 and most recently manifesting in ASHRAE 90.1 (2016) have produced a series of step-wise improvements that have led to a reduction in anticipated modelled EUI of almost 50%, excluding ASHRAE 90.1: 2016 (see Fig. 1).

ASHRAE 90.1 is commonly thought by designers as being an assessment of the energy savings of the designed building against a baseline building, it is in fact the energy COST savings. And this is where the situation starts to get somewhat muddy – especially if our metric of building performance is carbon emissions rather than energy cost. Imagine a simple scenario where a building exists in a region with an electrical supply primarily from renewable energy and a natural gas network. If the building owner wants to save money, heating would be by gas boiler and distributed hot water. If he wants to save carbon, he'd use electric heating provided from renewable energy. Indeed, the ASHRAE baseline building assumes that heating is undertaken using gas boilers as they are the most cost effective way to provide heat. Therefore the designer is penalized for using a less carbon intense heating source. Cost efficiency trumps emissions. It should be noted that USGBC recently released an alternative compliance path that allows scoring toward LEED credits to be assessed using carbon dioxide emission as a metric (USGBC, 2017).

Nevertheless there is a significant movement of cities, regions and countries to promote the development of net zero energy buildings. By mid-2016 there were more than 330 net-zero energy buildings (completed or planned) in the United States (New Buildings Institute, 2016). The American Institute of Architects (AIA) established the AIA2030 commitment whereby signatory architecture firms commit to designing 100% of their buildings to be net zero energy by 2030. Other similar programs include the Architecture 2030 challenge (and associated 2030 districts). Achieving the 2030 goals largely relies on going beyond building code and to a great extent on having clients willing to spend additional time and money on design and construction. Predicting how much an advancement beyond the model code - ASHRAE 90.1, a net zero energy building will be in 2030 is impossible to do with any degree of confidence, nevertheless for illustrative purposes only, Fig. 2 does suggest that it is conceivable that code improvements will continue toward the 2030 target.

As carbon dioxide has become established as a metric for building energy performance, so has the increasing popularity and desire for so-called net zero carbon build-

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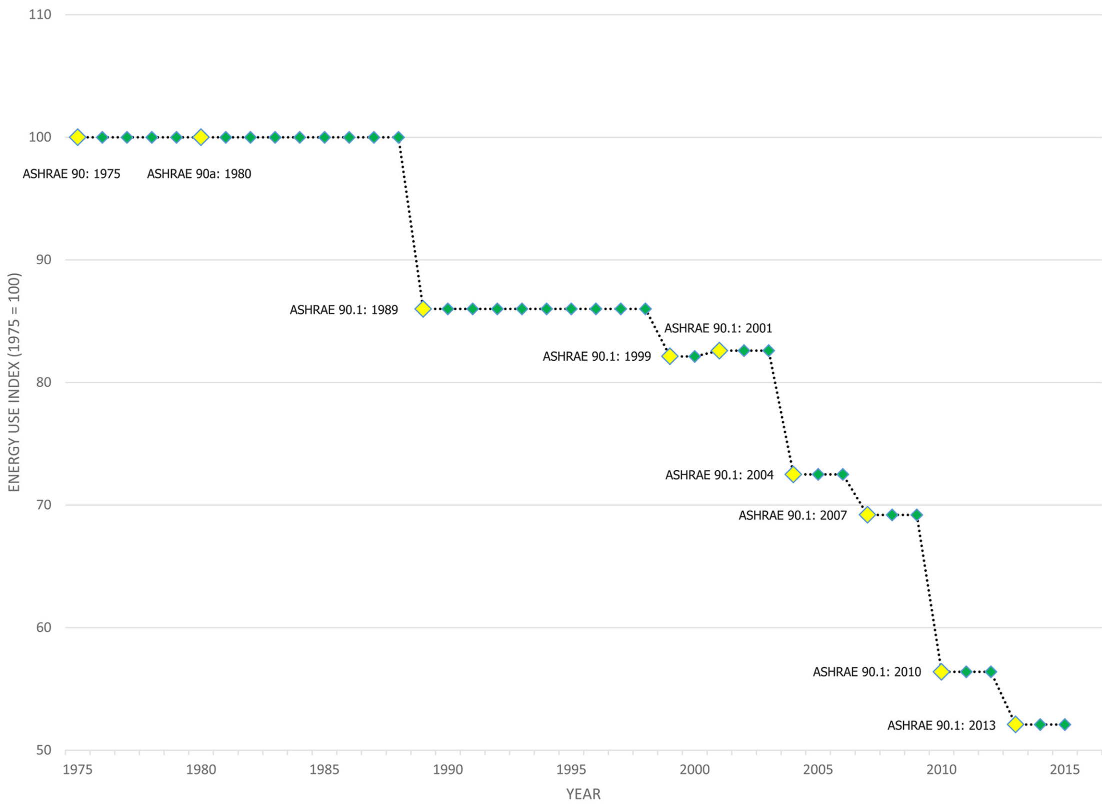


Figure 1. Improvement in ASHRAE standard 90.1 (1975-2013). Produced from PNWL data.

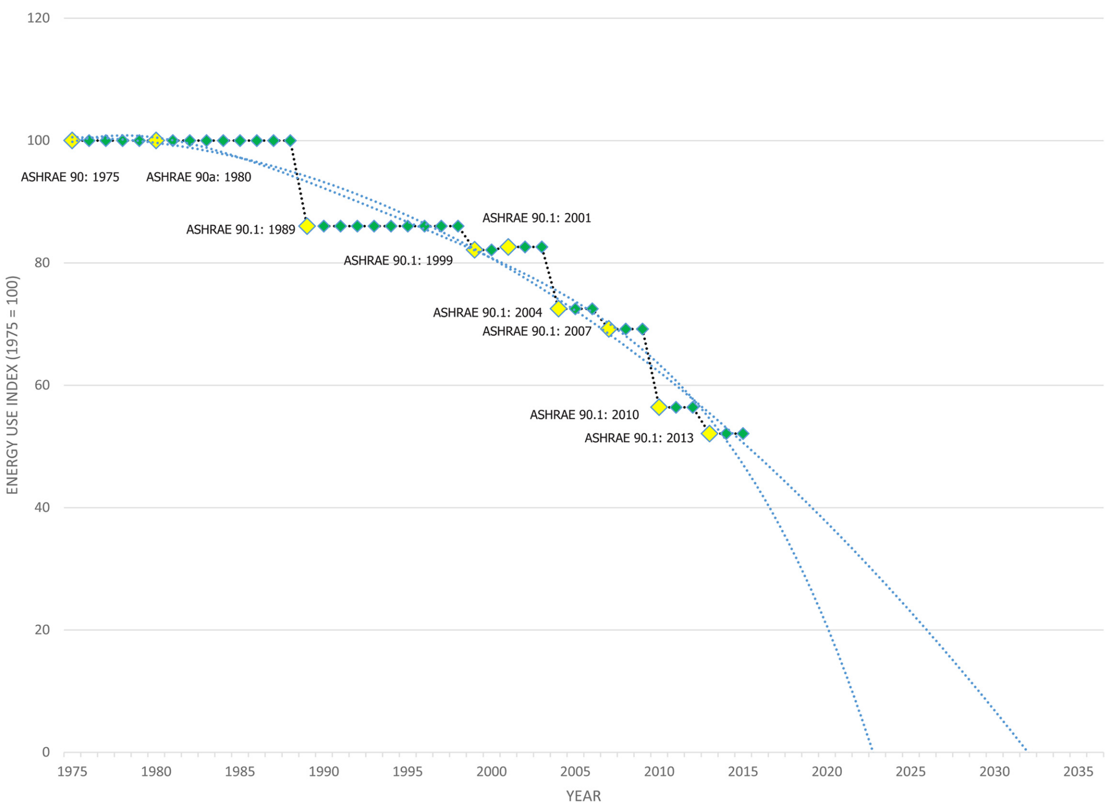


Figure 2. Projected potential timeline for ASHRAE 90.1: 20XX to require net zero energy buildings.

ings.

Although there are multiple definitions of carbon neutral, the one thing that all definitions have in common is that all operational carbon emissions should be balanced by an equivalent amount being offset (through onsite or offsite renewables). The general consensus is that the phrases carbon neutral and net zero carbon are the same thing, with some definitions differing in their boundaries. The AIA, for example, has definitions for net zero operations, net zero operations and embodied carbon and net zero operations, embodied carbon and occupant transport. Meanwhile Architecture 2030 defines a zero net carbon buildings as a highly energy efficient building that produces on-site, or otherwise procures, enough carbon free renewable energy to meet building operations' energy consumption annually (Architecture 2030, 2017).

As buildings approach very low Energy Use Intensities (EUIs) and the energy supply needed to meet the remaining demand transitions to cleaner sources [Fig. 3], the savings in carbon emissions for the investment rapidly enter the phase of diminishing returns and the embodied carbon component of the building – the emissions associated with product manufacture, transportation and construction – become all the more significant. In fact, to achieve operational carbon neutrality the 'carbon cost of the building may even increase due to the fact that the building envelope requires more insulation through addition of additional insulation material and additional glass in moving from double to triple glazed fenestration. Furthermore, whereas operational emissions occur over the entire lifetime of the building, emissions arising from the construction of the building occur within a very short period of time and nothing that we do or change once the building is operational can be done to reduce that amount. All that can ever be done is to offset it. In many cases materials are manufactured in locations that are distant from the point of use, so while it may serve one jurisdiction to be able to claim carbon neutrality, there is a much higher price being paid elsewhere and, globally, unless the building designer or contractor uses or specifies low embodied carbon materials, the overall contribution to carbon emission and therefore to climate change increases.

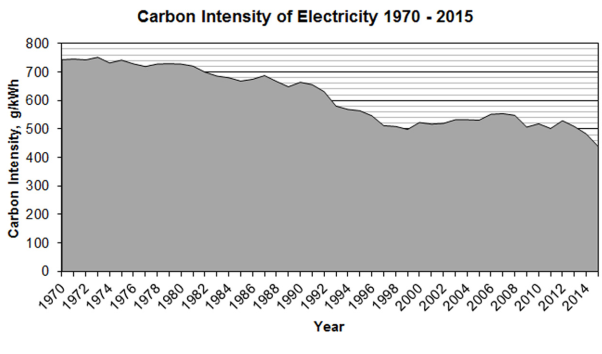


Figure 3. carbon intensity of electricity generated in the UK showing a 40% decrease in emissions per kWh since 1970.

2. Life Cycle Carbon Neutrality

Life Cycle analysis is the estimation of carbon dioxide throughout the entire building life cycle from extraction of raw materials, manufacture of products, construction, operations and maintenance and through to demolition and disposal or recycling. Although typically referring to products only, it is also used at a building scale. At this point, there emerges some slight ambiguity. When LEED V4 awards points for whole of building life cycle assessment reduction, the operational emissions of the building are not considered – the approach taken is to require that both baseline and proposed buildings have the same energy performance and that it is excluded from the LCA calculation.

We are unambiguous in our definition of life cycle carbon neutrality or life cycle net zero carbon:

A life cycle net Zero carbon building is one for which the carbon dioxide emissions associated with the construction, operation and maintenance of the building over a defined period of time have been accounted for and have been offset through a combination of on-site energy production, on site carbon sequestration and offsite purchase of green energy credits or other carbon offsets.

The purpose of the exercise described below was to determine the most appropriate pathway to take the design for an energy efficient commercial building and then rework it in order for it become a life cycle net zero carbon building.

The project site was located in Vancouver, BC, Canada. The City of Vancouver is considered to be one the most progressive cities in the world in terms of climate change awareness and carbon emissions reduction strategies. The City has made a number of commitments at local, regional and global scales. A Zero Emissions Building Plan was published in July 2016, whereby the City council adopted a target to reduce emissions from new buildings by 90% compared to 2007 levels by 2025 and to achieve zero emissions for all new buildings by 2030. The same plan also included targets for Thermal Energy Demand Intensity as well as other initiatives.

In addition to the documented commitments, The City of Vancouver is a signatory to a number of regional and global initiatives, including:

1. The Carbon Neutral Cities Alliance
2. The C40 cities
3. 100 resilient cities
4. Pacific North America Climate Leadership Agreement
5. The Architecture 2030 commitment

Clearly the City of Vancouver is committed to leading North America in terms of carbon emissions reductions. It does have one very significant advantage over many other cities though… the carbon intensity of the energy grid in BC is very low as a consequence of most of the electricity being produced from hydroelectric energy – electricity emissions being 0.01 $kgCO_2e/kWh$, compared with, for example, 0.681 $kgCO_2e/kWh$ in the mid-west USA. Having such a low emissions factor allows operational carbon neutrality to become a realistic goal with much lower investment by the developers than in other cities where the carbon intensity of the grid is higher.

3. Road map - How to Get to Lifecycle Net Zero Carbon

3.1. Describing the Life-Cycle and the Boundaries

Describing the life cycle of the building and then agreeing on what aspects are included in the final estimation is a key organizing stage of the study (Fig. 4). For the purposes of this study, all contributing elements typically contained within an Environmental Product Declaration (EPD) - raw material through fabrication, commonly referred to as cradle to factory gate, were included in the calculation. Additionally we made an estimate of delivery emissions, factory gate to site, based on known locations of production / fabrication facilities.

The decision on which materials to include was based on prior experience of knowing which components make the greatest contribution to the overall embodied carbon of the building:

1. Building core
2. Columns
3. Floor slabs
4. Beams
5. Foundations
6. Facade components -
   a. Aluminum mullions
   b. IGUs
   c. Spandrel
   d. Insulation

We originally intended to include construction and installation emissions, but ultimately decided against it for the following reasons:

1. Each structural option necessitated a completely different construction approach
2. The database of construction emissions estimates were quite simply not accurate enough to allow a realistic estimate
3. The construction and installation carbon emissions are minimal compared to the other stages of the Life Cycle of the building.

Operational emissions are a key component and were calculated on an annual basis. The remaining components of the life-cycle estimate – maintenance and end of life, were excluded based on lack of accurate precedent data.

3.2. Defining the building

Gross Building Area: 40,000 m^2
Above Grade Area: 37,250 m^2
Below Grade Area: 2,900 m^2
Building Height: 127.1 m
Number of levels: 26 stories +1 basement

Embodied carbon emissions were calculated for structural and exterior wall elements of the Building design. A Revit model of the building was used to quantify material quantities and Tally®, a plug in for Revit BIM software, was used to calculate the embodied carbon.

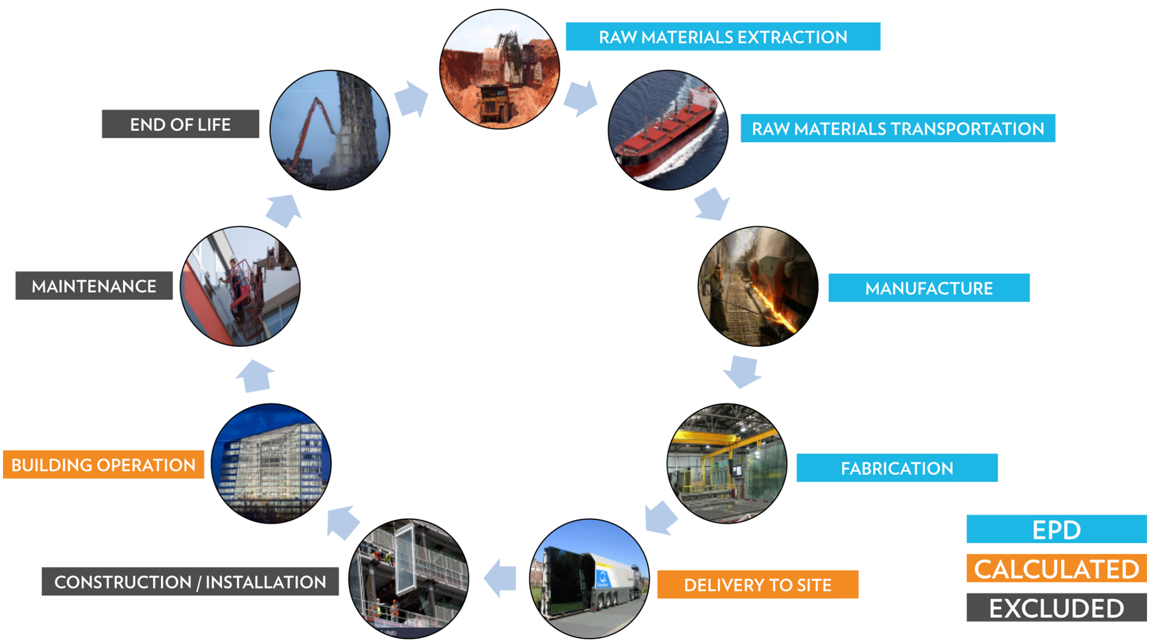


Figure 4. Describing the life cycle and boundaries.

Energy modeling using EnergyPlus was used to calculate the energy demand of one year of operation of the building and the equivalent operational carbon emissions corresponding to the type of fuels used to operate the building: electricity and natural gas.

3.3. Structural baseline and structural options

The baseline structural elements consist of a concrete building core, metal deck with concrete topping for the floors, steel girders and cross beams, steel columns, and concrete foundations.

In addition to the baseline, four structural options (A through D) were studied based on discussions with structural engineers. Two main strategies related to the building structure were identified to help achieve carbon neutrality: utilize wood to the greatest extent possible since it offsets carbon dioxide, and replace the concrete core with an all steel core that can potentially contain a lower embodied carbon.

The options defined consisted of variations of the main structural elements of the baseline design: a steel core, a composite floor slab of Cross Laminated Timber (CLT) deck with concrete topping and replacing the steel beams with glulam beams.

Option A: The metal deck with concrete topping is replaced with a composite wood and concrete structural floor. The steel cross beams are replaced with glulam beams.

Option B: Same as Option A, except the steel cross beams are kept in case penetrations through the glulam beams for mechanical ductwork becomes structurally challenging.

Option C: The concrete core is replaced with a steel core. The metal deck with concrete topping is replaced with a composite wood and concrete structural floor. The steel cross beams are replaced with glulam beams.

Option D: Same as Option C, except the steel cross beams are kept in case penetrations through the glulam beams for mechanical ductwork becomes structurally challenging.

For all of these options a higher content of cement replacement in concrete is considered. These options are summarized in Fig. 5.

3.4. Identify and Optimize Materials for Embodied Carbon of the Building

For all structural materials (steel, concrete and wood) AS+GG looked at three different material selection scenarios:

1. Typical materials - conventional materials with no prioritization of embodied carbon. Emissions factors based on industry averages. These materials were used for the baseline calculations.
2. Responsibly sourced materials - materials sourced based on lower embodied carbon. Commonly available although not necessarily locally.
3. Aspirational materials. Significantly reduced embodied carbon. Materials are theoretically available although a specific supplier was not identified.

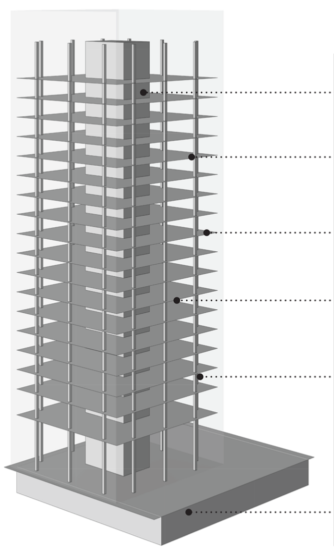
Emissions factors for the materials used in the calculations are shown in the Table 1. In order to allow a fair comparison against the baseline building exterior wall performance, we did not optimize exterior wall materials.

3.5. Exterior Wall Baseline and Exterior Wall Options

A baseline exterior wall and five different options were used to perform energy calculations on the Building.

Baseline The baseline exterior wall consisted of a double glazed assembly with a 65:35 vision to opaque ratio.

Five external wall options were studied as strategies to improve the energy performance of the building. These



	BASELINE	OPTION A	OPTION B	OPTION C	OPTION D
Building Core	Concrete	Concrete	Concrete	Steel	Steel
Floor Slabs	Metal Deck w/Concrete Topping	CLT/GLTs w/ Concrete Topping	CLT/GLTs w/ Concrete Topping	CLT/GLTs w/ Concrete Topping	CLT/GLTs w/ Concrete Topping
Girders	Steel	Steel	Steel	Steel	Steel
Cross Beams	Steel	Glulam	Steel	Glulam	Steel
Columns	Steel	Steel	Steel	Steel	Steel
Cement Replacement	20% Fly Ash/ GGBS	>20% Fly Ash/ GGBS	>20% Fly Ash/ GGBS	>20% Fly Ash/ GGBS	>20% Fly Ash/ GGBS
Foundations	Concrete	Concrete	Concrete	Concrete	Concrete

Figure 5. Structural system for Baseline design and 4 design options.

Table 1. Emissions factors for materials and transportation

CONSTRUCTION MATERIALS EMISSION FACTORS

	MATERIALS EMISSION FACTORS			MATERIALS TRANSPORTATION		
	TYPICAL MATERIALS CO2 Emissions Factor (kgCO2 eq/kg)	RESPONSIBLY SOURCED CO2 Emissions Factor (kgCO2 eq/kg)	ASPIRATIONAL CO2 Emissions Factor (kgCO2 eq/kg)	Mode of Transport	CO2 Emissions Factor (kgCO2 eq/km)	Distance - Plant to site (km)
BUILDING STRUCTURE MATERIALS						
Concrete (25 Mpa)	0.14	0.15 - 0.10*	0.08	Truck	0.43	24
Concrete (35 Mpa)	0.22	0.19 - 0.14*	0.12	Truck	0.43	24
Concrete (50 Mpa)	0.24	0.22 - 0.17*	0.13	Truck	0.43	24
Reinforcing Steel	1.16	0.07	0.07	Rail	0.04	5,000
Steel Deck	1.47	0.21	0.21	Rail	0.04	5,000
CLT Panels	-1.60	-1.60	-1.60	Truck	0.43	389
Glulam Beams	-1.28	-1.28	-1.28	Truck	0.43	389
Structural Steel	1.47	0.19	0.19	Rail	0.04	5,000
EXTERIOR WALL MATERIALS						
Double Pane IGU (Argon filled)	1.40			Truck	0.43	940
Triple Pane IGU (Argon filled)	1.71			Truck	0.43	940
Triple Pane IGU with Electrochromic Glass	50.82			Truck	0.43	940
Single Pane Glass Low-E	1.30			Truck	0.43	940
St. Steel Composite Panel	2.30			Truck	0.43	25
Anodized Alum. Frame	6.57			Truck	0.43	663
Insulated Glass Spandrel Panel	1.91			Truck	0.43	940
Spandrel Panel with laminated PV	2.29			Truck	0.43	940
Metal Screen Panels	2.34			Truck	0.43	418
SBS Roofing	1.11			Truck	0.43	172
Rigid Insulation (R-20)	2.67			Truck	0.43	1,299

* 30% cement replacement - 50% cement replacement

options were: a 65:35 triple glazed system, a 65:35 with an improved double glazed system, a 60:40 triple glazed system, a ventilated double wall facade, and a triple glazed electrochromic glass system. These options are described next and glass performance values for all options are listed in the table below.

Option 1 A vision to opaque ratio of 65:35 is kept as in the baseline. The double glazed system is replaced with a triple glazed system with an improved thermal insulation (u-value) and a reduced solar heat gain coefficient (SHGC), which prevents solar radiation from being transmitted into the building. The u-value of the spandrel is also improved.

Option 2 The vision to opaque ratio is kept at 65:35. A double glazed system with a lower u-value and SHGC is selected. The u-value of the spandrel is also improved.

Option 3 The vision to opaque ratio is reduced to 60:40. A triple glazed system with a lower u-value and SHGC is selected. The u-value of the spandrel is also improved.

Option 4 A ventilated double wall with a 250 mm air space is utilized. The air space between the inner and outer skins serves as a thermal buffer for the building. Stack effect in the cavity helps to draw in cool air from operable louvers when needed. In addition, blinds located within the cavity are used as a superior shading strategy. The u-value of the spandrel is also improved.

Option 5 A vision to opaque ratio of 65:35 is kept as in the baseline. A triple glazed electrochromic glass system is utilized. The electrochromic glass transitions seamlessly between multiple tint states significantly reducing unwanted solar heat, while still letting natural light in. The u-value of the spandrel is also improved.

These options are summarized in Fig. 6.

3.6. Alternative PV Wall Baseline and Alternative PV Wall Options

Building Integrated Photovoltaics (BIPV) systems were studied for the spandrel panels of the facade for the baseline and exterior wall options, except option 4 (double skin facade), as a means of producing electricity on site and therefore, further reducing the grid electricity demand of the building.

The performance of the glass of each alternative option is kept the same as in the exterior wall baseline and exterior wall options described on the previous section.

These alternative wall options differ from the exterior wall baseline and options described on the previous section only in that they include BIPV within the spandrel panel. The alternative options are summarized in Fig. 7.

3.7. Operational carbon emissions

Whole building energy modeling was used to estimate the annual energy demand of the building and the operational carbon and energy cost associated with it. Energy simulation was carried out using EnergyPlus software within the Design Builder interface.

The analysis was based on the Building 2015 design and the baseline exterior wall as well as the five exterior wall options were studied to estimate potential energy and operational carbon reductions. The baseline mechanical

	BASELINE	OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5
Vision to opaque ratio	65 / 35	65 / 35	65 / 35	60 / 40	N/A	65 / 35
Glazing system	Double Glazed	Triple Glazed	Double Glazed	Triple Glazed	Ventilated Double Wall	Electrochromic Glass
U-value (W/m^2K)	1.6	1.0	1.2	1.0	1.2	1.0
SHGC	0.28	0.21	0.22	0.21	0.22	0.22 - 0.09
Spandrel U-value (W/m^2K)	0.250	0.143	0.143	0.143	0.143	0.143
LEED - LEED Energy Points	Platinum - 6 points	Platinum - 7 points	Platinum - 7 points	Platinum - 8 points	Platinum - TBD	Platinum - TBD

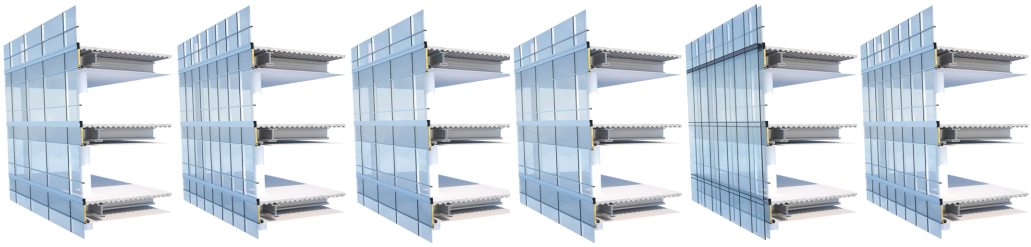


Figure 6. Curtainwall system for Baseline design and 5 design options.

	ALTERNATIVE PV BASELINE	ALTERNATIVE PV OPTION 1	ALTERNATIVE PV OPTION 2	ALTERNATIVE PV OPTION 3	ALTERNATIVE PV OPTION 5
Vision to opaque ratio	65 / 35	65 / 35	65 / 35	60 / 40	65 / 35
Glazing system	Double Glazed	Triple Glazed	Double Glazed	Triple Glazed	Electrochromic Glass
U-value (W/m^2K)	1.6	1.0	1.2	1.0	1.0
SHGC	0.28	0.21	0.22	0.21	0.22 - 0.09
Spandrel U-value (W/m^2K)	0.250	0.143	0.143	0.143	0.143
LEED - LEED Energy Points	Platinum - 6 points	Platinum - 7 points	Platinum - 7 points	Platinum - 8 points	Platinum - TBD

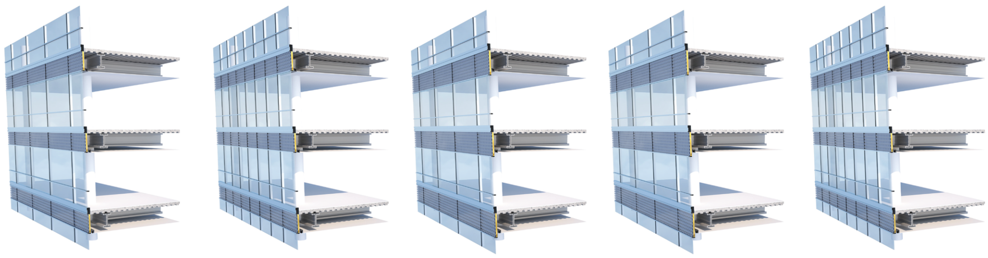


Figure 7. Alternative curtainwall system with renewables incorporated for Baseline design and 5 design options.

system - Fan coil unit with ECM VSD with high efficiency chillers with gas fired condensing boilers, was used in conjunction with the baseline exterior wall. For the exterior wall options, an alternative mechanical system with all-electrical components was used - Fan coil unit with ECM VSD with ASHP with electric boiler back up.

The grid emissions factors used in the calculations were obtained from the "2016/17 B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions" report published by the Victoria, B.C. Ministry of Environment in May 2016. These emissions factors are:

- Electricity: 0.0107 kgCO2 eq/kWh
- Natural Gas: 0.1781 kgCO2 eq/kWh

Also, the blended electricity and gas rates established by Fortis B.C. Energy Inc. were used in the calculations of the annual energy cost. These rates are:

- Electricity: 0.091 $/kWh
- Natural Gas: 0.026 $/kWh

3.8. Building Integrated Photovoltaics

Building Integrated Photovoltaics (BIPV) systems were studied for the roof of the building and the alternative wall options described earlier.

The PV spandrel consisted of double laminated safety glazing units with mono-crystalline silicon solar cells that will simultaneously serve as building envelope material and power generator. The efficiency of the spandrel PV was assumed to be 14.6% and 19% for the roof PV.

The estimated energy generation through PV, as well as the areas covered with PV, and the nominal power of the systems are shown on the following tables for facade options with a window to wall ratio of 65/35 and 60/40.

4. Results and Discussion

4.1. Operational Energy

The operational carbon of the Building was calculated

Table 2. Operational emissions

	BASELINE	EXTERIOR WALL OPTION 1	EXTERIOR WALL OPTION 2	EXTERIOR WALL OPTION 3	EXTERIOR WALL OPTION 4	EXTERIOR WALL OPTION 5	ALTERNATIVE WALL OPTION 1	ALTERNATIVE WALL OPTION 2	ALTERNATIVE WALL OPTION 3	ALTERNATIVE WALL OPTION 5
Annual Energy Demand										
Electricity (kWh)	3,787,294	3,790,149	3,796,240	3,780,791	3,428,133	3,775,067	3,358,003	3,364,094	3,331,551	3,342,921
Natural Gas (kWh)	821,441	0	0	0	0	0	0	0	0	0
Total Energy Demand (kWh)	**4,608,736**	**3,790,149**	**3,796,240**	**3,780,791**	**3,428,133**	**3,775,067**	**3,358,003**	**3,364,094**	**3,331,551**	**3,342,921**
Energy Use Intensity (kWh/m2)	**139.8**	**115.0**	**115.2**	**114.7**	**104.0**	**114.5**	**101.9**	**102.1**	**101.1**	**101.4**
Annual Operational Carbon										
Electricity (kg CO2eq)	40,359	40,389	40,454	40,289	36,531	40,228	35,784	35,849	35,502	35,623
Natural Gas (kg CO2eq)	146,267	0	0	0	0	0	0	0	0	0
Total Operational Carbon (kg CO2eq)	**186,625**	**40,389**	**40,454**	**40,289**	**36,531**	**40,228**	**35,784**	**35,849**	**35,502**	**35,623**
Operational Carbon Intensity (kg CO2eq/m2)	**5.7**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.1**	**1.1**	**1.1**	**1.1**
Annual Energy Cost										
Electricity Cost ($)	344,644	344,904	345,458	344,052	311,960	343,531	305,578	306,133	303,171	304,206
Natural Gas Cost ($)	21,056	0	0	0	0	0	0	0	0	0
Total Energy Cost ($)	**365,700**	**344,904**	**345,458**	**344,052**	**311,960**	**343,531**	**305,578**	**306,133**	**303,171**	**304,206**
Energy Cost Intensity ($/m2)	**11.1**	**10.5**	**10.5**	**10.4**	**9.5**	**10.4**	**9.3**	**9.3**	**9.2**	**9.2**

Table 3. Structural system embodied carbon

			STRUCTURE OPTIONS							
	BASELINE		OPTION A		OPTION B		OPTION C		OPTION D	
STRUCTURE: Building Core	Concrete		Concrete		Concrete		Steel		Steel	
STRUCTURE: Floor Slabs	Metal deck w/concrete topping		CLT/GLTs w/concrete topping		CLT/GLTs w/concrete topping		CLT/GLTs w/concrete topping		CLT/GLTs w/concrete topping	
STRUCTURE: Girders	Steel		Steel		Steel		Steel		Steel	
STRUCTURE: Cross Beams	Steel		Glulam		Steel		Glulam		Steel	
STRUCTURE: Building Columns	Steel		Steel		Steel		Steel		Steel	
STRUCTURE: Cement Replacement	Fly Ash / GGBS		Fly Ash / GGBS		Fly Ash / GGBS		Fly Ash / GGBS		Fly Ash / GGBS	
STRUCTURE: Foundations	Concrete		Concrete		Concrete		Concrete		Concrete	
	Responsibly Sourcing	Aspirational	Responsibly Sourcing	Aspirational	Responsibly Sourcing	Aspirational	Responsibly Sourcing	Aspirational	Responsibly Sourcing	Aspirational
EMBODIED CARBON (Tons CO2 eq)	**16,009**	**6,306**	**4,288**	**1,985**	**5,124**	**2,822**	**2,065**	**804**	**3,807**	**1,571**
Reduction Against Baseline	**N/A**	**60.6%**	**73.2%**	**87.6%**	**68.0%**	**82.4%**	**87.1%**	**95.0%**	**76.2%**	**90.2%**

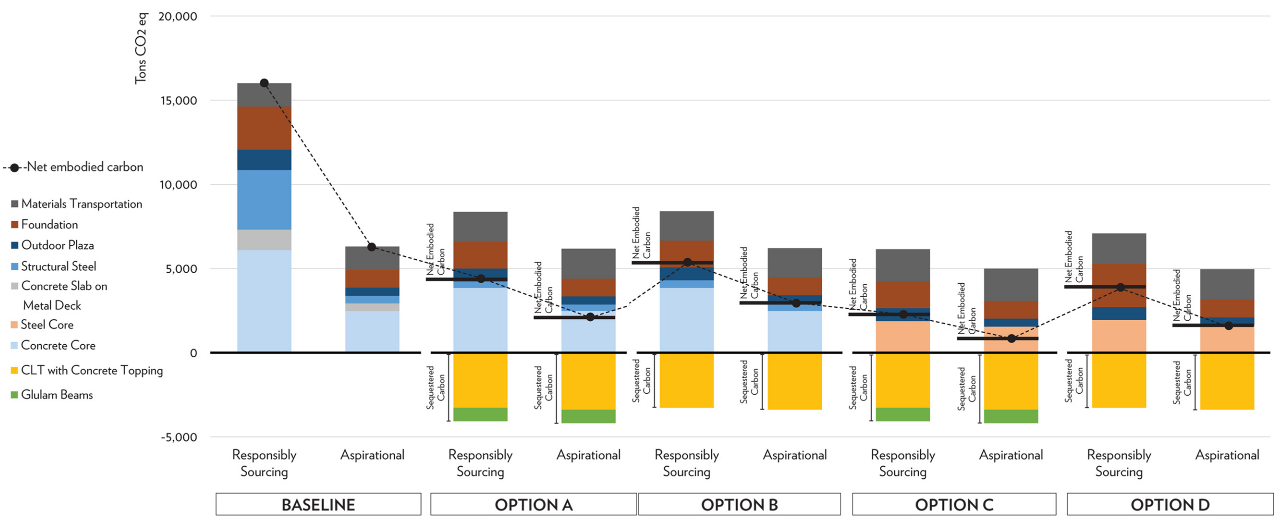


Figure 8. Structural embodied carbon.

using the different exterior wall options with and without PV spandrel. The annual operational emissions using the baseline exterior wall were 187 tons of CO2 eq. The annual operational emissions were reduced to 36-40 tons of CO2 eq (without PV), and to 35 tons of CO2 eq for the options with PV spandrel and PV roof, representing a saving of up to 81%.

The building energy demand, operational carbon, and energy cost estimated for the baseline and various options is shown in Table 2.

4.2. Embodied carbon

The embodied carbon of the structural and exterior wall elements of the Building 2014 design was calculated for the baseline and different options. The studies showed that the embodied carbon of the baseline building was 16,009 tons CO2 eq. Through responsible sourcing of materials, the embodied carbon was reduced by 73% using a CLT composite deck with Glulam beams, and by 87% using a steel core. The embodied carbon for these same structural options was further reduced to 88% and 95% respectively with the aspirational sourcing. Results are summarized in Table 3 and Fig. 8.

The exterior wall studies showed that the embodied carbon of the baseline system was 1,587 tons of CO2 eq. The embodied carbon of the exterior wall options, excluding the electrochromic glass option which has a significantly higher embodied carbon, increased from 0-23%

Table 4. Exterior wall embodied carbon

		BASELINE	EXTERIOR WALL OPTIONS: OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5
EXTERIOR WALL	Glazed to opaque ratio	65/35 WWR	65/35 WWR	65/35 WWR	60/40 WWR	N/A	65/35 WWR
	Glazing system	Double Glazed	Triple Glazed	Double Glazed	Triple Glazed	Ventilated Double Wall Facade	Triple Glazed
	Glass type	VE46-1 W/ARGON	TBD	TBD	TBD	TBD	Electrochromic Glass
	U-value	1.6 W/m2K	1.0 W/m2K	1.2 W/m2K	1.0 W/m2K	IGU U-VALUE: 1.2 W/m2K	1.0 W/m2K
	SHGC (IGU)	0.28	0.21	0.22	0.21	IGU SHGC: 0.22	0.22 - 0.09
	SHGC (single pane)	N/A	N/A	N/A	N/A	0.79	N/A
	Spandrel U-value	0.250 W/m2k	0.143 W/m2k	0.143 W/m2k	0.143 W/m2k	0.143 W/m2k	0.143 W/m2k
	LEED	Platinum	Platinum	Platinum	Platinum	Platinum	Platinum
	LEED Energy Points	6	7	7	8	TBD	TBD
MEP	Mechanical System type	Fan coil unit w/ECM VSD with High Efficiency chillers with condensing boilers	Fan coil unit w/ECM VSD with ASHP with electric boiler back up	Fan coil unit w/ECM VSD with ASHP with electric boiler back up	Fan coil unit w/ECM VSD with ASHP with electric boiler back up	Fan coil unit w/ECM VSD with ASHP with electric boiler back up	Fan coil unit w/ECM VSD with ASHP with electric boiler back up

	BASELINE		OPTION 1		OPTION 2		OPTION 3		OPTION 4		OPTION 5	
	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof	Exterior Wall	Alternative Wall w/ PV Spandrel and PV Roof
EMBODIED CARBON (Tons CO2 eq)	1,587	1,622	1,939	1,976	1,587	1,622	1,931	1,978	1,960	N/A	20,699	20,736
Embodied Carbon Increase	N/A	2.2%	22.1%	24.5%	0.0%	2.2%	21.6%	24.6%	23.5%	N/A	1203.9%	1206.2%

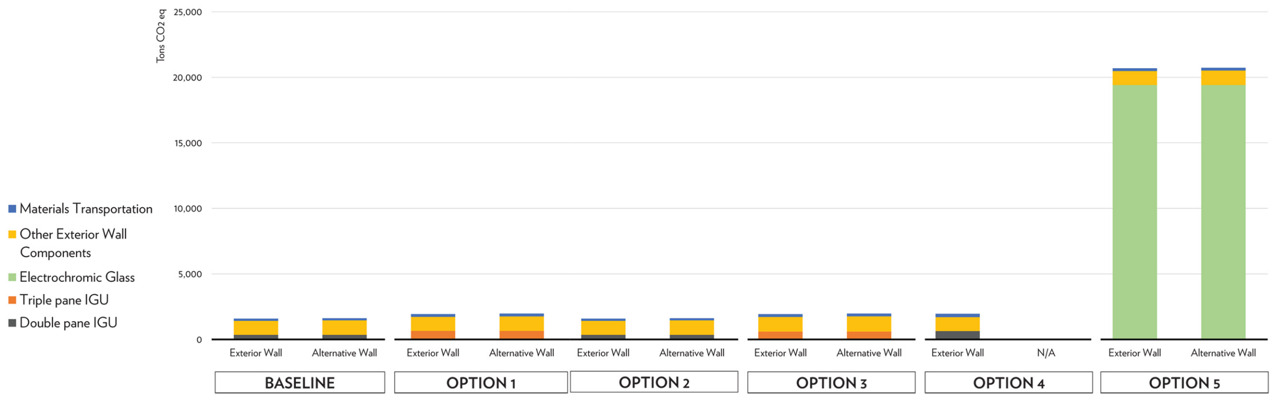


Figure 9. Exterior wall embodied carbon.

when compared to the baseline, and from 2-25% for the options with PV spandrel and PV roof. Results are summarized in Table 4 and Fig. 9.

4.3. Life Cycle Carbon neutrality

Each structural option was paired with each exterior wall option; that is: the baseline structure, four structural options using responsibly sourced materials, and the baseline and four structural options using aspirational materials were combined with the baseline exterior wall, five exterior wall options, the baseline and exterior wall options with PV roof, and the baseline and four exterior wall options with PV spandrel and PV roof. This resulted in a total of 170 different combinations. For each of these combinations, the following parameters were calculated:

- Total Embodied Carbon (tons CO2 eq) - Based on AS+GG calculations.
- Annual Operational Carbon (tons CO2 eq) - Based on AS+GG calculations.
- Capital Cost Premium ($) - Based on cost calculations provided by cost consultant.
- Annual Operational Cost ($) - Based on AS+GG calculations.
- Embodied Carbon Offsets ($) - Based on AS+GG embodied carbon calculations assuming a rate of US $1.40 / ton CO2
- Operational Carbon Offsets ($/year) - Based on AS+GG operational carbon calculations assuming a rate of US$1.40 / ton CO2

These calculations for the 170 combinations of options are presented as a scatter plot (Fig. 10) showing the relationship between the life cycle carbon emissions (embodied carbon + 10 years of operational carbon) and the life cycle cost (capital cost premium + 10 years of operational cost) for the 170 combinations of options.

Using a 65:35 window to wall ratio with a high performance glass, double glazed façade, roof PV and sourcing low embodied carbon materials showed that life cycle carbon emissions over 10 years could be reduced from 19,462 to 6,271 tons CO2, representing a reduction of 68%. The cost premium for doing this is estimated to be $8,994,500 but would also realize annual operational cost savings of $40,177, representing a reduction of 11%.

The 68% lifecycle reduction includes a marginally improved concrete emissions reduction. An 80% lifecycle carbon reduction can be achieved through reducing the embodied carbon of concrete to aspirational levels which have been achieved elsewhere in North America through using higher concrete replacement volumes and other strategies.

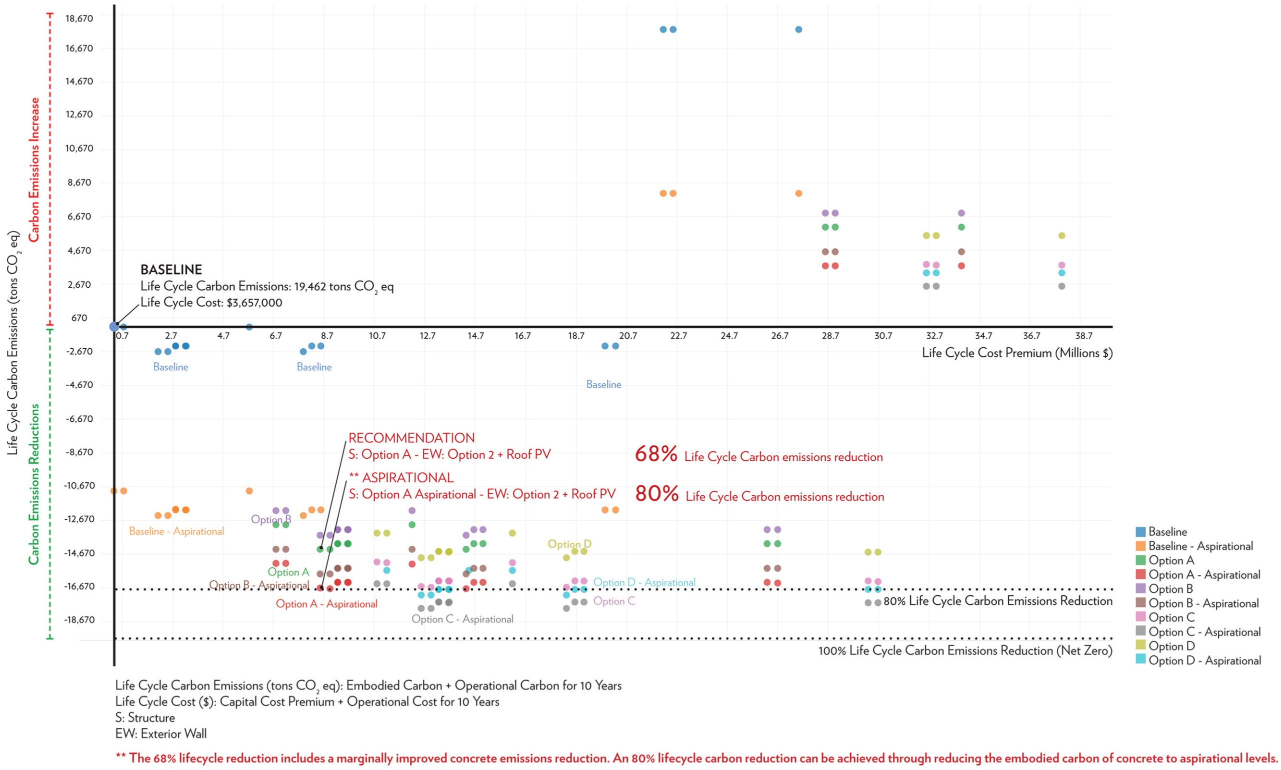


Figure 10. Scatter plot of 170 possible combinations of envelope, structure and material improvement.

If life cycle cost was not an issue then Option C delivered an 86.4% reduction in life cycle carbon emissions – leaving just 2,391 tons of embodied carbon and 40 tons of carbon per year from operational emissions to be offset. We believe that reducing life cycle carbon emissions to the extent that has been shown to be economically viable and offsetting the remainder through an accredited offset scheme meets the intent of the definition of carbon neutrality and therefore we suggest that designing life cycle net zero buildings should be discussed as a future target for architects advocating for the reduction of atmospheric CO_2 emissions.

5. Conclusion

If life cycle cost was not an issue then Option C would be the preferred route as it delivered an 86.4% reduction in life cycle carbon emissions – leaving just 2,391 tons of embodied carbon and 40 tons of carbon per year from operational emissions to be offset.

The challenge with targeting life cycle carbon neutrality is that there is no direct economic payback for the cost and time expended in reducing embodied carbon. A building made of concrete with 60% GGBS replacement of cement has no real operational cost savings over a building made with 100% Ordinary Portland Cement. For there to be any benefit requires legislation (in the form of building codes or material standards) or some form of incentive.

Reducing embodied carbon through codes and standards is a multi-step process and, unsurprisingly, nowhere in the world has a code mandated whole building life cycle emissions reduction requirement. However some countries have taken steps to do so, at least at a component level. Establishing an embodied carbon value for a construction material or an assembly is the first stage. This is achieved through preparing an Environmental Product Declaration (EPD). EPDs are prepared following an ISO standard (ISO 14025: 2006), the boundaries and methods for establishing product specific EPDs follow what is known as a Product Category Rule (PCR) the PCR process is also covered by an ISO standard (ISO 29130: 2007).

EPDs are making their way into building codes in Europe, according to the web page of Bionova (the software company that produces the LCA tool Oneclick ® - Belgium requires the use of EPDs if a company is performing any environmental-related marketing. France is moving towards the general adoption of LCA requirements for the whole construction industry, while in the Netherlands it is already established and Finland is currently creating a roadmap to include the building materials' impacts into the legislation.

The Marketing aspect is currently the most powerful incentive for building developers to reduce embodied carbon. Reducing the embodied carbon of the structure and enclosure by 10% gets 3 points in USGBCs LEED rating scheme following Option 4. Whole-Building Life-Cycle Assessment of the Materials and Resources credit - Building Life-Cycle Impact Reduction. A further improvement in the other impact factors considered in an LCA gets an exemplary point. As stated above, in order to quantify a whole building LCA, an EPD for the materials used should have been prepared and this in turn is also rewarded under the LEED scheme – getting 2 points (3 with exemplary performance) for providing EPDs and demonstrating a reduction against a product average. These points all have a marketing value, but also an economic value. If a developer had to achieve the 7 points through some other means in order to get a platinum rated building – for example energy saving, then he'd have to consider something like an improvement in energy performance from 24% to 46%, which would almost certainly have a very significant [capital] cost associated with it (although there would of course be an operational cost saving).

Another approach can be incentives provided to developers from the local planning authorities. It's not hard to imagine a scenario where, in return for a developer providing a planning jurisdiction with a means of reducing their overall carbon emissions in line with some highly publicized target or simply just giving them bragging rights for leadership in whole building carbon emissions reductions, the authorities allow reward them with a Floor to Area Ratio bonus (basically allowing the developer to build more leasable floor space), or perhaps fast track planning approval for the building, allowing the developer to build faster and start to get a return on investment sooner.

We believe that this study shows that reducing life cycle carbon emissions to a significant extent has been shown to be economically viable, and further reducing emissions to near zero is very feasible. Offsetting the remainder through an accredited offset scheme meets the intent of the definition of carbon neutrality and therefore we suggest that designing life cycle net zero buildings should be discussed as a future target for architects advocating for the reduction of atmospheric CO_2 emissions.

As a footnote, all AS+GG projects in the United States and the Middle East have specification language that requires EPDs to be provided for concrete, steel and insulation materials. In taking this step we are applying the lessons learned from this study (and other earlier work) and are contributing to a gradual change in supply chain behavior and a consequent reduction in building life cycle carbon emission.

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